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ROADAPT
Roads for today, adapted for tomorrow

Guideline – Part C: GIS-aided vulnerability assessment for roads

– Existing methods and new suggestions

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CEDR Call2012: Road owners adapting to climate change

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Guideline – Part C: GIS-aided vulnerability assessment for roads – Existing methods and new suggestions

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Table of contents

Executive summary

The ROADAPT project is part of the CEDR Call *Road owners adapting to climate change*. This guideline describes efficient existing tools for assessing vulnerabilities to climate change related threats within the TEN-T network. The guideline is targeted at road-owner staff and consultants with responsibility for assessing the vulnerability of the road network to climate change-related risks.

In this project, an inventory of methods for detailed vulnerability assessment was conducted, showing that far from all climate-change related threats are covered by the existing methods. In response, a new comprehensive GIS-based vulnerability assessment methodology is suggested, Roadapt VA. The method is based on and compatible with the RIMAROCC method and can be used integrated with RIMAROCC or stand-alone. The output of the vulnerability analysis is spatially distributed vulnerability index scores in the form of a GIS dataset. The vulnerability map is easy to use together with additional GIS data. For Roadapt VA to be ready-to-use the method should be tested in case studies. In order to be accessible for a wider public, the method should be complemented with ready-to-use vulnerability scoring tables for all climate change-related risks.

Furthermore, recommendations on priorities of data sources for transnational and regional/national scale studies are given. An inventory on transnational GIS datasets for mapping the vulnerability factors show that many contextual site factors are available on an international scale, while most infrastructure intrinsic factors seem to be available only on road-owner scale or on national scale. Data recorded by road owners themselves constitute a major gap in transnationally harmonised GIS data.

Using the tools and methods described in this guideline, it should be possible to assess vulnerability to all climate change-related threats within the TEN-T road network.

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1 Introduction

Infrastructures are the backbone of our society. Citizens, companies and governments have come to rely on and expect uninterrupted availability of the road network. Extreme weather is an important factor for the reliability and safety of the road network. At the same time it is generally understood that the climate is changing and that this will have significant effects on the road infrastructure. Since road infrastructure is vital to society, climate change calls for timely adaptation.

Although there are considerable uncertainties involved in both the projections of future climate change and related socio-economic developments and in estimations of the consequences of these changes in transportation needs, there is a constant need for decisions and development of the road transport system. As stated in the CEDR 2012 Climate Change DoRN: *'Road authorities need to evaluate the effect of Climate Change on the road network and take remedial action concerning design, construction and maintenance of the road network.'*

The ROADAPT project is part of this CEDR Call. ROADAPT has an integral approach following the RIMAROCC (Risk Management for Roads in a Changing Climate) framework that was developed for ERA NET ROAD in 2010. ROADAPT aims at providing methodologies and tools enabling tailored and consistent climate data information, a good communication between climate researchers and road authorities, a preliminary and fast quick scan for estimating the climate change related risks for roads, a vulnerability assessment, a socio economic impact analysis and an action plan for adaptation with specific input from possible adaptation techniques related to geotechnics and drainage, pavements and traffic management.

Outputs of the ROADAPT project are guidelines that address all these topics. In the main guidelines an overview of all topics is provided. In five following parts the specific topics are addressed in detail. These five parts are:

A. Guidelines on the use of climate data for the current and future climate
B. Guidelines on the application of a QuickScan on climate change risks for roads
C. Guidelines on how to perform a detailed vulnerability assessment
D. Guidelines on how to perform a socio economic impact assessment
E. Guidelines on how to select an adaptation strategy

The underlying guideline is part C.

1.1 Target Audience

This report is targeted at road-owner staff and consultants with responsibility for assessing the vulnerability of the road network to climate-change related risks. Risk assessment skills are required for in-depth understanding. For chapter 3, knowledge of GIS analysis and risk assessment is required for in-depth understanding of the methods described.

1.2 Objective

The objective is to describe efficient existing tools for assessing vulnerabilities within road networks, with a focus on networks managed by National Road Authorities and specifically TEN-T Network roads. In addition, a new comprehensive vulnerability assessment methodology is suggested, based on and compatible with the RIMAROCC method. The vulnerability maps created in the process should be possible to combine with detailed climate change projections. Using the tools and methods described, it should be possible to assess vulnerability to all climate change-related threats within the TEN-T road network. Furthermore, guidance to transnational vulnerability assessment and existing GIS data sources is provided.

1.3 Considerations for vulnerability assessment method development

A ROADAPT workshop with road-owners within the TEN-T network was organised in Delft, the Netherlands, on April 22-23, 2013. One important outcome of the workshop was the road-owners' descriptions of what their ideal vulnerability assessment method would be capable of. The desired qualities of a vulnerability assessment method can be summarized:

- Formulas for vulnerability index calculation for each threat. Not in detail, and based on outcomes of existing projects related to each climate event. Not dependent on the probability of occurrence of the climatic event.
- Results of vulnerability analysis are presentable as a map with possibility to add additional information.
- Information on what GIS datasets are needed for vulnerability assessment of each climatic risk, and where to find data.
- Description of which vulnerabilities can be assessed with world/EU-scale GIS data, and which needs detailed national GIS data.
- Guide on how to put together two different datasets at country borders. Information on what data from national road databases must be harmonized in order to enable cross-border vulnerability assessment.

1.4 Two approaches to vulnerability assessment

There is a range of methods available for vulnerability assessment of climate-induced threats. The starting point of this project was to inventory the existing methods and assess their applicability for vulnerability assessment of roads. These methods are listed in Chapter 2 along with information on the considered threat. In Annex C necessary input data, output of method and a link to additional information on the method are listed. Looking at the inventory results, it became clear that the existing methods are not covering all threats and that there is a need for a general vulnerability assessment method that covers the remaining climate-induced threats.

The goal of the method developed within this project, the *Roadapt method for Vulnerability Assessment* (Roadapt VA), is to cover all climate-induced threats with the same method. Roadapt VA is described in Chapter 3.

The methods listed in Chapter 2 are developed to assess vulnerability for one threat, and generally can provide a higher level of detail than Roadapt VA, in exchange for a heavier workload. When a high detail level is desired, it is advised to primarily look at the methods in Chapter 3.

Roadapt VA is recommended when the user wishes to get a good overview and visualization of vulnerable locations to one or more threats at a relatively low workload. When using the proposed international GIS datasets, Roadapt VA is suitable for transnational analyses. For threats where no detailed vulnerability assessment methods exist, Roadapt VA is recommended.

1.5 Use of RIMAROCC framework

In Bles et al. (2010) a method is described that road owners can use to do a climate change risk assessment. This is done by using 7 steps of the so called RIMAROCC framework (see figure below). These steps facilitate in the identification of risks due to a changing climate, together with the consequences of the risk. When risks are evaluated as being unacceptable for the road owner, risk mitigation has to take place, followed by implementation of action plans and monitoring of results. The RIMAROCC framework provides the general methodology that needs to be used on different levels of analysis (both geographical scale and level of detail). The methodology presented in this report is intended for use either integrated with RIMAROCC or as a more detailed vulnerability assessment following a Quickscan as described in Roadapt guideline part B.

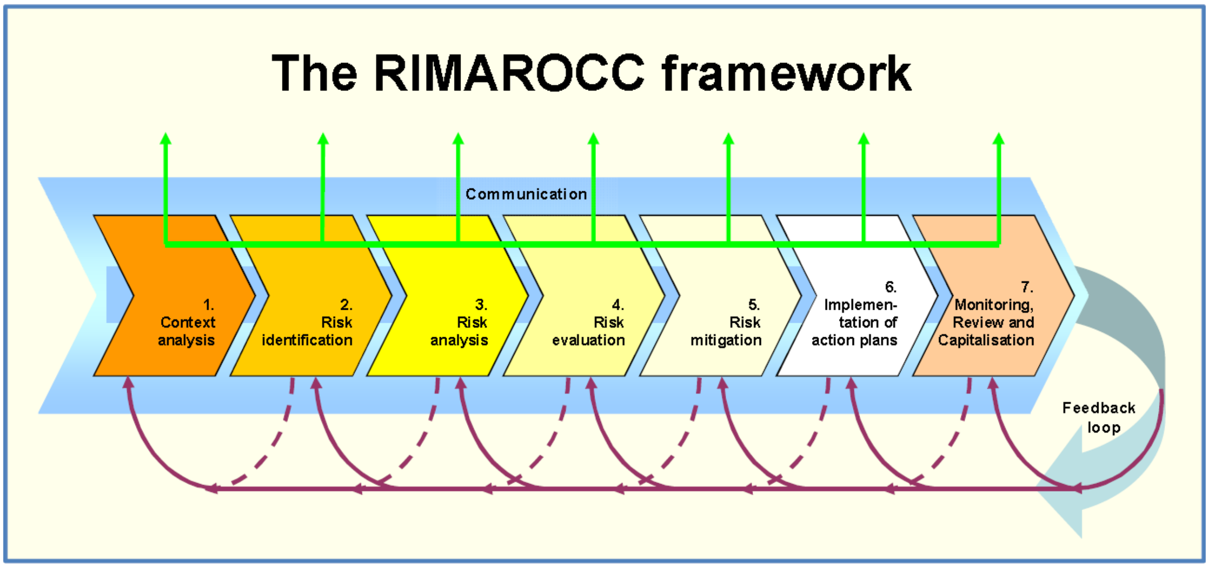


Figure 1. The RIMAROCC framework (Bles et al., 2010).

2 Existing GIS-aided vulnerability assessment methods

2.1 Guideline to using existing vulnerability assessment methods

This approach makes use of existing detailed vulnerability assessment methods for each threat and is really a guide to identify and select the appropriate detailed vulnerability assessment method for the threat that needs to be analysed. The methods presented in this chapter have been tested in case studies and/or applied in full-scale analyses.

An inventory of existing vulnerability assessment methods was performed by scanning CEDR publications and ERA-net Road publications and by web-search queries and SGI library search queries with the keywords “vulnerability assessment”, “vulnerability analysis” and “risk analysis”. The inventory should not be considered a comprehensive study. Inventory results show that there are useful vulnerability assessment methods for a range of threats and sub-threats, especially for the main-threats flooding and landslips. Some methods are developed specifically for roads while others are developed for overall vulnerability assessment. Many of the methods have been developed for national use, while some are intended for use in multiple countries. Most existing vulnerability assessment methods approach only one threat.

Information needs and relation to RIMAROCC

The procedure described below corresponds to RIMAROCC steps 2.1 “Identify risk sources” (contextual site factor identification) and 2.2 “Identify vulnerabilities”.

The starting point for the described method is that it is known which threats need detailed vulnerability assessment. When selecting which threats to include in the vulnerability assessment it is recommended to use information equivalent to one of the following points:

- QuickScan results: risk evaluation and prioritization results from Step 4.4 “Evaluate and prioritize the risks”. For further information on the QuickScan method, see Roadapt Guideline part B.
- RIMAROCC results from risk identification (RIMAROCC steps 1.1, 1.2, 1.3 and the climate factor identification in step 2.1). For further information on the RIMAROCC framework, see Bles et al. (2010).

Step 1: Select method for detailed vulnerability assessment

The described vulnerability assessment methods are sorted and named in accordance with the threat and sub-threat categories in Annex 1, Table A.2. For threats where no detailed vulnerability assessment method has been identified, it is recommended either to use the Roadapt VA method (Chapter 3), or to proceed with vulnerability assessment according to the RIMAROCC method, Step 2.2.

Existing methods for detailed vulnerability assessment within each climate risk are described in a separate table (Annex C). The table includes information on:

- Threat
- method name
- analysis output
- necessary input data
- reference to method description

An overview of threats and available methods is given in Table 1.

Table 1. Overview of climate change-related threats and applicable detailed vulnerability assessment methods.

Sub-threat	Vulnerability assessment method								
	Risk inventory for roads using national DTM and other databases	Identification of areas with prerequisites for landslides	Landslide risk model for the Norwegian road network*	The Blue Spot Model - Level 1	The Blue Spot Model - Level 2	The Blue Spot Model - Level 3	SGI Erosion index along coasts and watercourses	IRWIN	Dutch blue spot application
Slides of the road embankment	x								
External slides, ground subsidence or collapse, affecting the road		x							
Snow avalanches			x						
Rock fall			x						
Debris flow			x						
Pluvial flooding (overland flow after precipitation, increase of groundwater levels, increase of aquifer hydraulic heads)				x	x	x			x
Flooding due to failure of flood defence system of rivers and canals									x
Aquaplaning in ruts due to precipitation on the road, splash and spray									x
Erosion of road embankments							x		
Cracking due to weakening of the road base by thaw								x	
Reduced ice removal planability								x	
Icing and snow								x	
Reduced snow removal planability								x	

* The landslide risk model for the Norwegian road network is under development.

Example: In the Öresund region, between Denmark and Sweden, pluvial flooding has been identified as a threat. Table 1 then suggest that The Blue Spot Model – Level 1-3, or the Dutch blue spot application, may be useful.

Step 2: Gather input data

Necessary input data for the selected vulnerability assessment method are listed in Annex C along with information on output of the method and a reference to the method description. Guidance on how to find input data is provided in Chapter 4 and Annex B.

Example: Continuing with the example of pluvial flooding in the Öresund region, the table in Annex C point out that the following information is needed to conduct The Blue Spot Model – Level 1-3:

- *Level 1:*
  - Digital Terrain Model (DTM) or hydroadapted DTM
  - Catchment area polygons.
- *Level 2:*
  - Blue Spot Level 1 results
  - DTM or hydroadapted DTM
  - Catchment area polygons
  - Morphology data
  - Land use map
  - Local or national metrological data with return periods of precipitation scenarios.
- *Level 3:*
  - Blue Spot Level 2 results
  - Hydroadapted DTM
  - Local or national metrological data with return periods of precipitation scenarios
  - Road drainage systems
  - Traffic loads
  - Alternative routes
  - etc.

Step 3: Assess vulnerability

Execute the method and map the vulnerability. For compatibility with RIMAROCC, the output can be presented either as a list of vulnerable locations or as a map.

Example: Performing the Blue Spot Analysis Level 1 by using the input data as suggested in step 2 results in a GIS-layer showing the spots in the Öresund region sensitive to pluvial flooding.

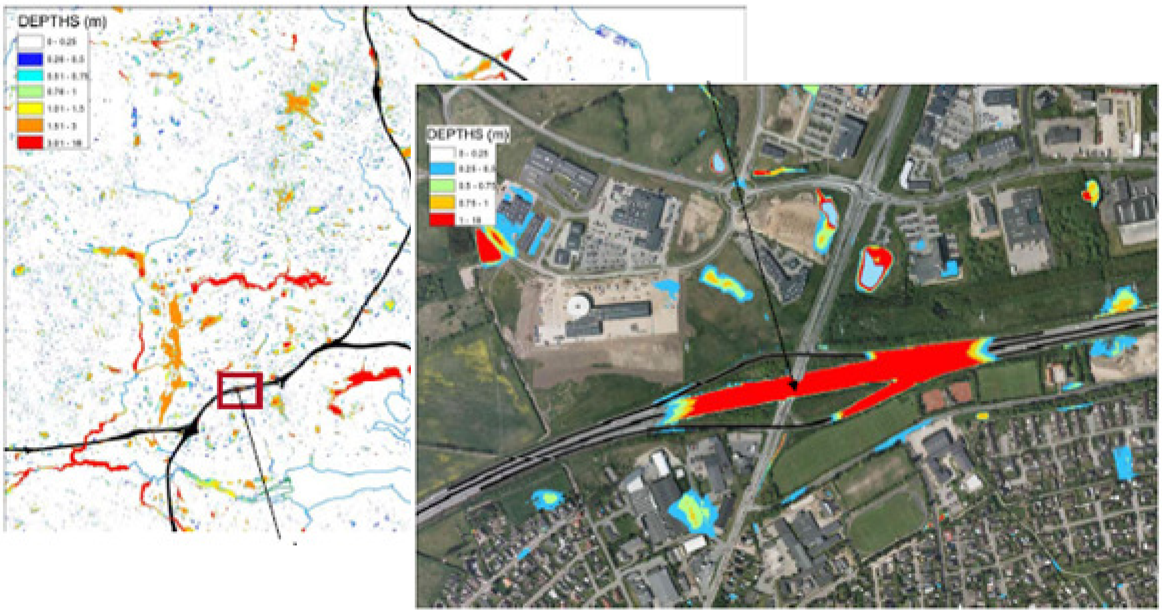


Figure 2. Identified Blue spots (Level 1) showing their area, volume and depth (example from ROADAPT case study Öresund).

2.2 *Evaluation of existing vulnerability assessment methods*

The results from the inventory of existing methods (Annex C) show that GIS-aided vulnerability assessment methods are missing for a large part of the climate change-related threats that the TEN-T network is facing. In response to this, a draft version of a new method, Roadapt VA, has been outlined in this project and is described in chapter 3.

3 Proposition for a Roadapt method for Vulnerability Assessment

3.1 Introduction

The range of climate-change related threats for roads presents a great variety of related vulnerability factors. The proposed *Roadapt method for Vulnerability Assessment* (Roadapt VA), is based on the RIMAROCC method and utilizes GIS to systematically map, organize and visualize these vulnerability factors. The output of Roadapt VA is a map showing spatially distributed vulnerability index for the studied threat along a section or a network of TEN-T roads. The degree of vulnerability is presented as a green-to-red color ramp with values ranging from 0 (no vulnerability) to 100 (maximum vulnerability).

Roadapt VA can be used stand-alone, or with RIMAROCC as a replacement for the following RIMAROCC steps:

- Sub-step 1.3 - Establish risk criteria and indicators adapted to each particular scale of analysis (vulnerability indicator identification only)
- Sub-step 2.1 Identify risk sources (contextual site factor identification only)
- Sub-step 2.2 Identify vulnerabilities

The method described in this chapter should not be considered ready-to use. It is a proposed draft method for assessing vulnerabilities for multiple climate change-related threats. For Roadapt VA to be ready-to-use the method should be tested in case studies.

Roadapt VA requires skills within GIS analysis as well as road vulnerability assessment. If two persons are needed to cover these skills it is recommended to conduct the analysis in close cooperation.

3.2 Definitions

ROADAPT uses the same risk definition as the RIMAROCC framework: risk is a function of threat, vulnerability and consequences. Vulnerability is also defined in the same way in both methods: a function of sensitivity, exposure and adaptive capacity. Infrastructure-intrinsic factors can be referred to as «sensitivity», and contextual site factors can be referred to as «exposure». Adaptive capacity is something global and transversal, for infrastructure-intrinsic factors it mainly depends on the road owner/operator means, so we can assume that – for a given road owner/operator – it will be the same whatever the threat. Therefore adaptive capacity is not stressed in the suggested method; although some of the vulnerability factors in Annex A, Table A.1 can be considered as adaptive capacity.

The presentation of vulnerability factors differ in RIMAROCC and Roadapt VA. In RIMAROCC, the contextual site factors are handled in step 2.1 “Identify risk sources” as part of the threat, whereas in Roadapt VA they are handled together with the infrastructure intrinsic factors (Figure 3). Keep this in mind when using Roadapt VA in combination with the RIMAROCC framework in order to avoid double-counting the contextual site factors.

Vulnerability to a climate-related threat is described using contextual site factors and infrastructure intrinsic factors. The contextual site factors describe the area surrounding the road: vegetation, topography, geology, hydrography etc. The infrastructure intrinsic factors describe the road and road-related constructions: pavement, road embankment, foundation, bridges, drainage systems, erosion protection works etc. GIS datasets are used to visualize both the contextual site factors and the infrastructure intrinsic factors. Datasets covering the different contextual site factors can be provided by international or governmental organizations, regional authorities or private companies. Infrastructure-intrinsic factors are most often produced and owned by the road-owner or its associated organizations. Some vulnerability factors indicate whether the road is vulnerable or not to a specific threat, i.e. the factor is a prerequisite that needs to be fulfilled for an event to be possible. The other vulnerability factors are potential aggravating factors that can increase the vulnerability.

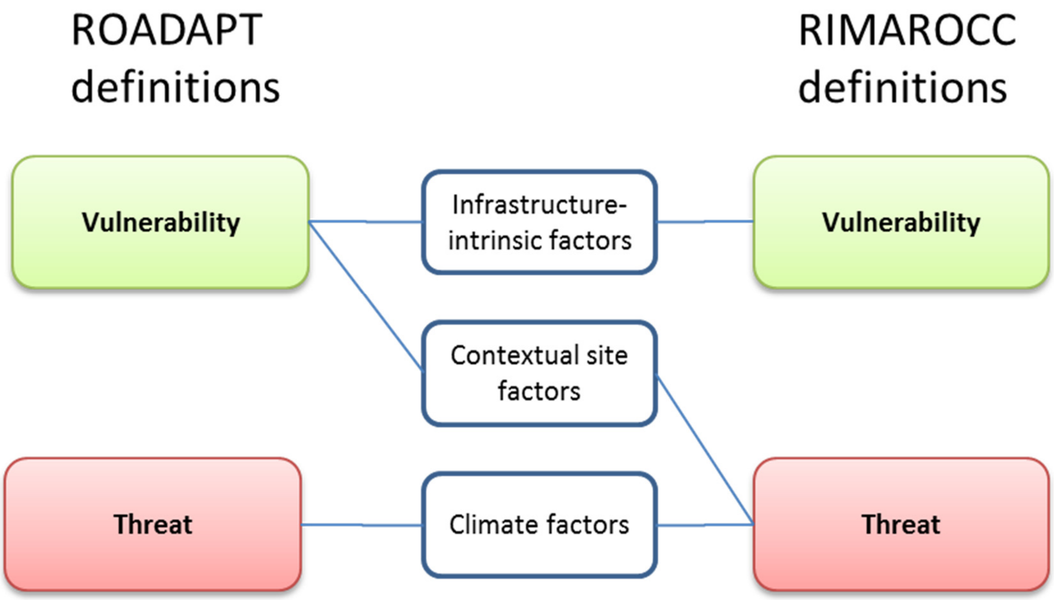


Figure 3. Schematic illustration of the definitions of vulnerability and threat in RIMAROCC and in ROADAPT VA.

3.3 Roadapt VA method description

The starting point of Roadapt VA is that it is known for which threat vulnerability should be assessed, and the geographic extents of the study area are known.

Information equivalent to one of the following points should be available:

- QuickScan results such as prioritized risk or identified main threat that need to be analysed in detail.
- RIMAROCC results from risk identification (RIMAROCC Step 1.1, 1.2, 1.3 and the climate factors from step 2.1).

Step 1: Defining vulnerability factors

Objectives of the step
The aim of this step is to define what vulnerability factor should be used in the vulnerability assessment.

Proposed sub-steps
Sub-step 1.1 - Identify relevant vulnerability factors

General recommendations for this step
Use the proposed vulnerability factors as a starting point, but take time to reflect on each factor. Is any vulnerability factor missing that is relevant for your road network and the studied threat? Is any vulnerability factor unnecessary, or impossible to assess, for the studied road network?

Sub-step 1.1: Identify relevant vulnerability factors

Use the vulnerability assessment tables (Annex A, Table A.1 and Table A.2) to identify the contextual site factors and infrastructure intrinsic factors that are relevant for vulnerability assessment of the selected threat. Identify which factors are *required* for the threat to occur and which factors can increase or decrease the vulnerability.

Example: Erosion of road bases and road embankments

The vulnerability factors for the threat "Erosion of road bases and road embankments" are found in Annex A, Table A.2 and are presented below. Since road bank geology was unknown, it was decided to replace this vulnerability factor with geology of natural soil. The vulnerability factors in Table A.1 are not included in this example.

Table 2. Identified vulnerability factors for road vulnerability assessment to erosion.

Vulnerability factors
Geology (soil type in natural soil)
Topography / slope angle
Observed erosion
Existing erosion protection barriers
Land cover / vegetation
Culvert/drum
Inspection interval
Hydrography

Step 2: Data collection

Objectives of the step
Collecting the necessary datasets. Missing GIS datasets are created from local knowledge, field inventories and map studies. Digitalization of manually created map information.

Proposed sub-steps
Sub-step 2.1 – GIS data inventory and collection
Sub-step 2.2 – Completing missing GIS datasets

General recommendations for this step
Vulnerability can be assessed even if one or more vulnerability factors are missing in your collected data after going through sub-steps 2.1 and 2.2. If so, go back to step 1 and adjust the vulnerability factors included in the vulnerability assessment. The excluded vulnerability factors should be documented. In subsequent steps of the risk management process (risk analysis, risk evaluation, risk mitigation) the effects of using an incomplete vulnerability index should be discussed.

Sub-step 2.1 – GIS data inventory and collection

Many vulnerability factors can be mapped using existing GIS datasets. However some purpose driven data need to be either generated from existing GIS datasets or digitized from paper maps and documentation to complement the input list, e.g. sun exposure could be generated from a digital elevation model and road base material could be digitized from road documentation records.

Depending on threat, analysis scale and geographic location of the study area, different GIS datasets may be used in the vulnerability assessment. Demands on resolution/scale of a certain vulnerability factor GIS dataset may differ depending on what threat is analysed. It is recommended to browse the available GIS datasets covering the vulnerability factor and then decide the appropriate scale for the study at hand.

For transnational studies it is recommended to use either the transnational GIS datasets summarized in Annex B, Table B.1, or the GIS datasets that are provided through the EU INSPIRE directive, Annex B, Table B.2. The INSPIRE datasets are created nationally but follow common definitions and themes, meaning that datasets from neighbouring countries are harmonized. For some vulnerability factors no transnational datasets are available and national datasets must be used.

If the study area is limited to one country it may be beneficial to use national GIS datasets: these may have higher resolution or include more attribute data than the datasets summarized in Annex B.

Example: Erosion of road bases and road embankments
Suitable existing GIS datasets are: digital elevation model (DEM), geology (soil map), land use, road network and hydrography network. The full set of source data is shown in Table 3.

Sub-step 2.2 – Completing missing GIS datasets

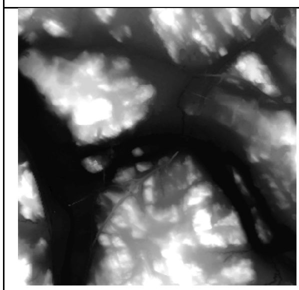
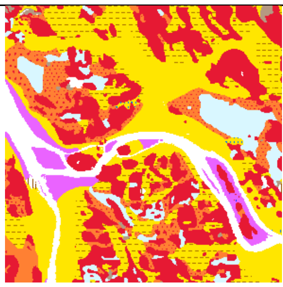
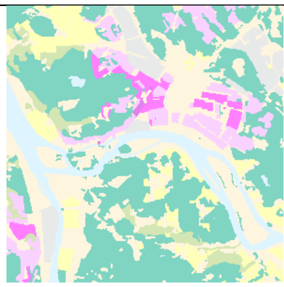
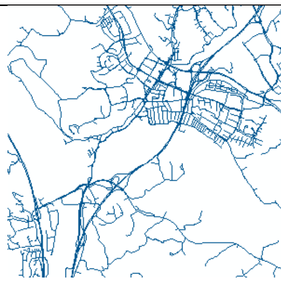
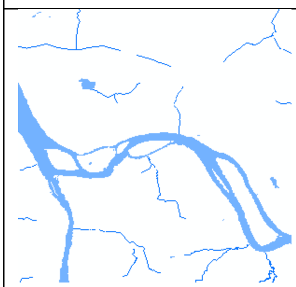
Input data that are not found as GIS datasets in step 2.1 must be created manually. Input data that is known but not mapped, e.g. expert knowledge, can be added either directly in GIS or noted on paper maps that are digitalized by a GIS technician. Input data that is unknown can be obtained from field inspections or from desktops studies. For desktop studies that are related to topography, it is recommended to generate a hill shade layer for overlay. Some suggested information sources are listed below:

- Road owner's databases
- Maintenance contractor records, database or knowledge
- Road inspection protocols
- Map desktop studies (e.g. using hill shade overlay to identify possible culvert locations)
- Field inspections

Example: Erosion of road bases and road embankments

The following datasets could not be obtained in step 2.1: culvert/drum locations, observed erosion, existing erosion protection barriers, and inspection intervals. A hill shade layer was generated to identify likely culvert/drum locations. Information on observed erosion and existing erosion protection barriers can e.g. be found through road inspection protocols, maintenance contractor knowledge or field inspections. Minimum frequency of field inspections as well as maintenance contract boundaries could e.g. be found in the maintenance contract. In this way, three more layers (active erosion, erosion protection barriers and culverts) were digitized to further illustrate the vulnerability of roads in relation to erosion. The full set of source data is shown in Table 3.

Table 3. Source data used for calculating erosion vulnerability index, EVI.

DEM (ascii-grid, raster)	Soil map (vector, polygons)	Land use (vector, polygons)	Road network (vector, lines)
			
River network (vector, polygons, lines)	Active erosion (vector, polygons)	Erosion prot. barriers (vector, polygons)	Culverts (vector, polygons)
			

Step 3: GIS analysis

Objectives of the step
The first objective is to set up a scoring table where properties for each vulnerability factor are scored in relation to their contribution to vulnerability. Then the GIS layers from step 2 are combined with the vulnerability assessment scoring table into vulnerability score raster layers for each vulnerability factor. A vulnerability index map for the studied threat is then created through raster calculations.

Proposed sub-steps
Sub-step 3.1 – Reclassifying input data into vulnerability factor scores
Sub-step 3.2 – Raster calculations
Sub-step 3.3 – Documentation

General recommendations for this step
In raster calculations, the cell size is a trade-off between desired resolution and analysis run-time. It is recommended to adapt the grid cell size to the study area so that a network scale analysis has a coarser grid than a road stretch scale analysis.

Sub-step 3.1 – Reclassifying input data into vulnerability factor scores

Steps should be taken to make all of the source data uniform in terms of format, resolution, spatial extent, attributes and classes. It is recommended to limit the spatial extent of the analysis to ~300m from the road in order to include vulnerabilities outside the immediate road area but still have sufficiently short analysis runtime in Sub-step 3.2.

To be of use in the vulnerability assessment, the GIS datasets need to be reclassified in order to display their respective contribution to the overall vulnerability. The information in the source data for each vulnerability factor should be classified into three different vulnerability scores: +2 (considerably increases vulnerability), +1 (increases vulnerability) and 0 (does not increase vulnerability). Document the reclassification in a vulnerability score table.

All the source data (that is not of raster format) must then be converted into raster data with correct pixel values via class-code identification and re-classification based on parameters from a look-up table (LUT). The look-up tables are the links between the information in the various GIS layers collected in step 2 and the vulnerability score table described above.

The output of this step is datasets illustrating each vulnerability factor's contribution to the overall vulnerability to the investigated threat.

Example: Erosion of road bases and road embankments
The studied road stretch is ~6 km long and the surrounding area within 300m from the road was included in the GIS analysis. For this limited spatial extent a detailed scale with grid cell size of 2m is possible.

A vulnerability score table is shown in Table 4. An example of reclassification from source layer attribute data into vulnerability scores is given in Table 5 The resulting classified and properly formatted (refined) pixel maps are shown in Table 6.

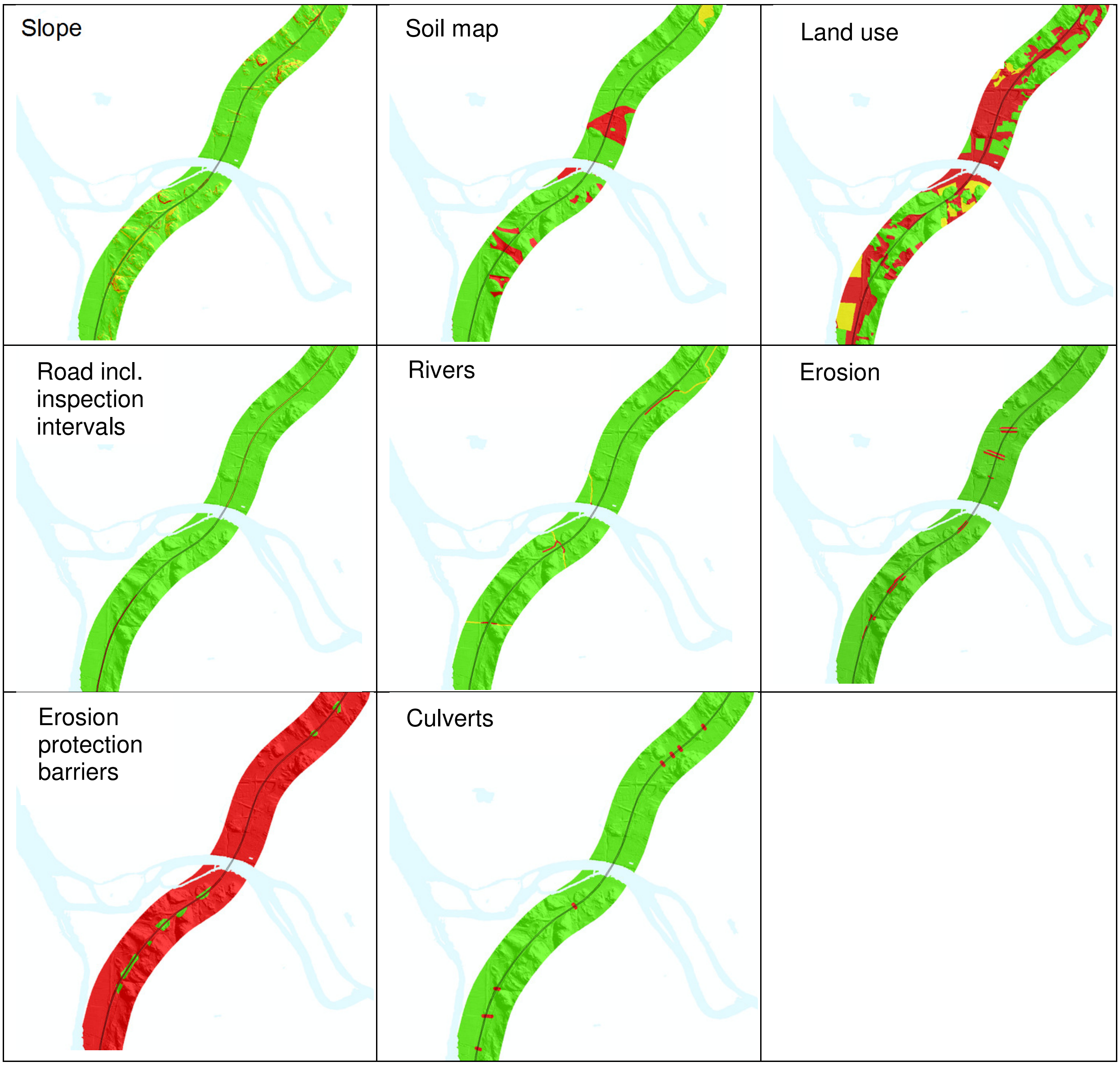
Table 4. Vulnerability assessment scoring table for calculations.

Vulnerability factor	Vulnerability score		
	0	+1	+2
Geology (soil type in natural soil)	Material with low sensitivity to erosion (sedimentary rock, till, clay)	Somewhat erosive material (gravel, coarse sand, silty till, clayey silt, silty clay, peat)	Highly erosive material (fine and medium sand, silt, flood-plain deposits)
Topography/slope angle	less than 1:3	1:1.5 - 1:3	more than 1:1.5
Observed erosion	No	-	Yes
Existing erosion protection	Yes	-	No
Land cover / vegetation	Forest, built-up areas, paved surface, dense vegetation	Arable land, scarce vegetation, solitary trees	disused arable land, other open land, very scarce vegetation, bare soil
Culvert/drum	No culvert or drum crossing road	-	culvert or drum crossing road within 20m from point of evaluation
Inspection interval	Road is inspected more than once per 1 years	Road is inspected every 2-5 years	Road is inspected less than once per 5 years
Hydrography	Distance to watercourse is more than 300m	Distance to watercourse is 100 - 300m	Distance to watercourse is less than 100m

Table 5. Look-up table: Identification of soil map class-codes (Code) and reclassification into vulnerability scores (Reclass).

Soil type	Code	Reclass
Peat	5	1
Flood-plain deposit, clay - silt	9	2
Postglacial fine clay	19	0
Postglacial fine sand	28	2
Postglacial medium - coarse sand	29	2
Glacial fine clay	43	0
Water	91	2
Sandy till	95	0
Fill	200	1
Bedrock	890	0

Table 6. Source data when reclassified into vulnerability scores and rasterised; green = 0, yellow = 1, red = 2.



Sub-step 3.2 – Raster calculations

The key process consists of calculating the normalized sum of a fixed set of input layers. The calculation in each raster cell can be formulated as:

$$VI = \frac{\sum_{i=1}^{n} VS_n}{\sum_{i=1}^{n} VSmax_n} * 100$$

Where

- VI = vulnerability index ($0 \leq VI \leq 100$)
- VS_n = vulnerability score for layer n
- $VSmax_n$ = maximal possible vulnerability score for layer n
- n = number of vulnerability factor layers

The output is a raster layer where each cell has a vulnerability index from 0 to 100. It is recommended to use a color ramp (e.g. green to red) to visualize the results.
If desirable, a weighting procedure can be added in this sub-step to take into account the relative importance of the vulnerability factors. By using weighting factors, you can increase or reduce the importance of the different vulnerability factors when the overall vulnerability score is calculated. Assign weights for each vulnerability factor from 0 to 1 so that the weights all add up to 1.0.

Example: Erosion of road bases and road embankments

A vulnerability index map for the south-west corner of the study area is shown in Figure 4.

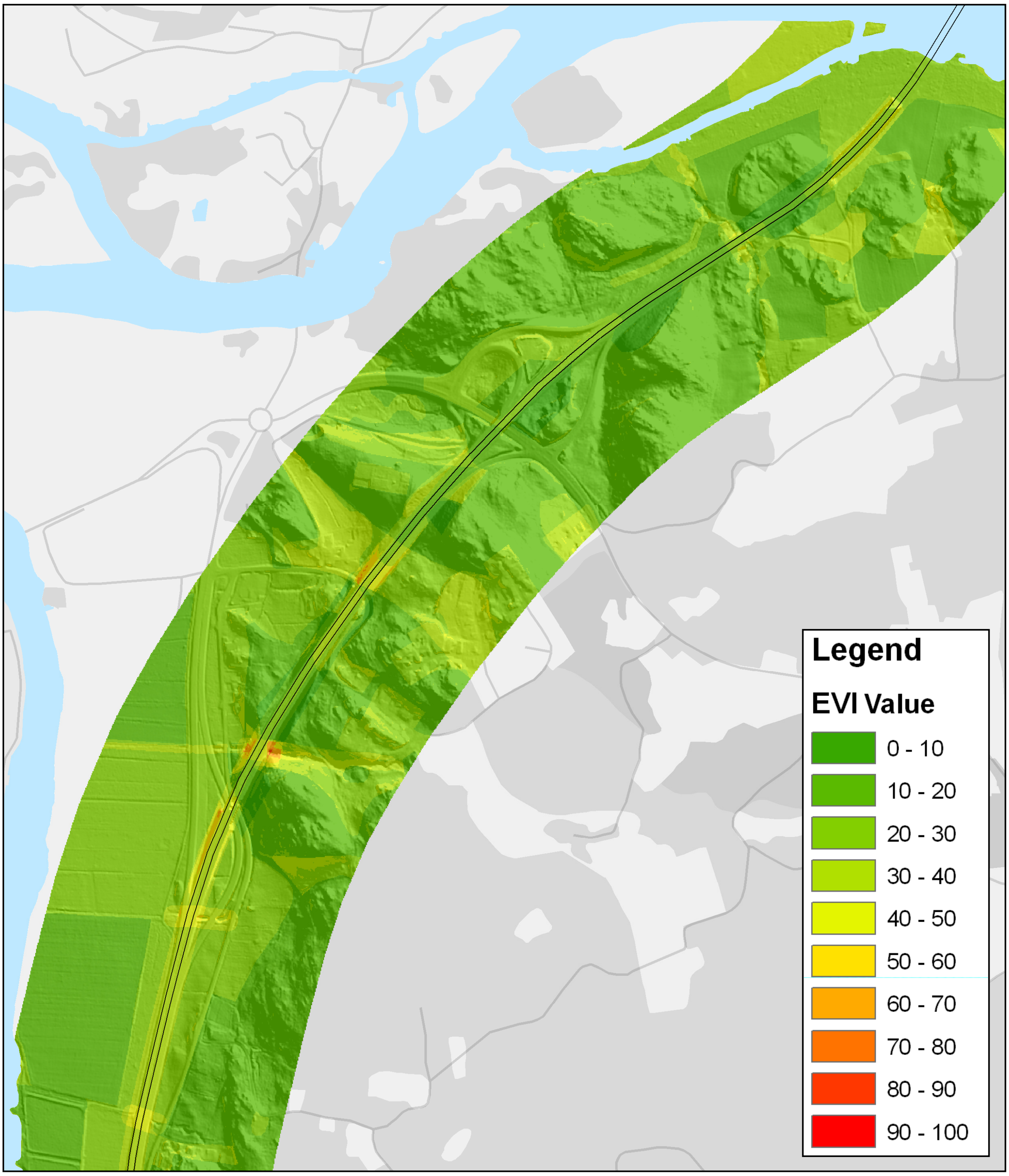


Figure 4. Erosion Vulnerability Index (EVI) map for the south-west corner of the study area.

Sub-step 3.3 – Documentation

For the analysis to be transparent, the following information should be documented:

- Selected vulnerability factors
- Data sources and their resolution/intended scale
- Vulnerability score table and look-up tables for reclassification
- The equation used for raster calculation
- Vulnerability score layers for each vulnerability factor
- Vulnerability index map
- Conceptual flowchart of the GIS processing steps taken to obtain the vulnerability index

Example: Erosion of road bases and road embankments

Examples are given in previous steps. A conceptual flowchart of the GIS processing steps taken to obtain the vulnerability index for roads to erosion is shown in Figure 5.

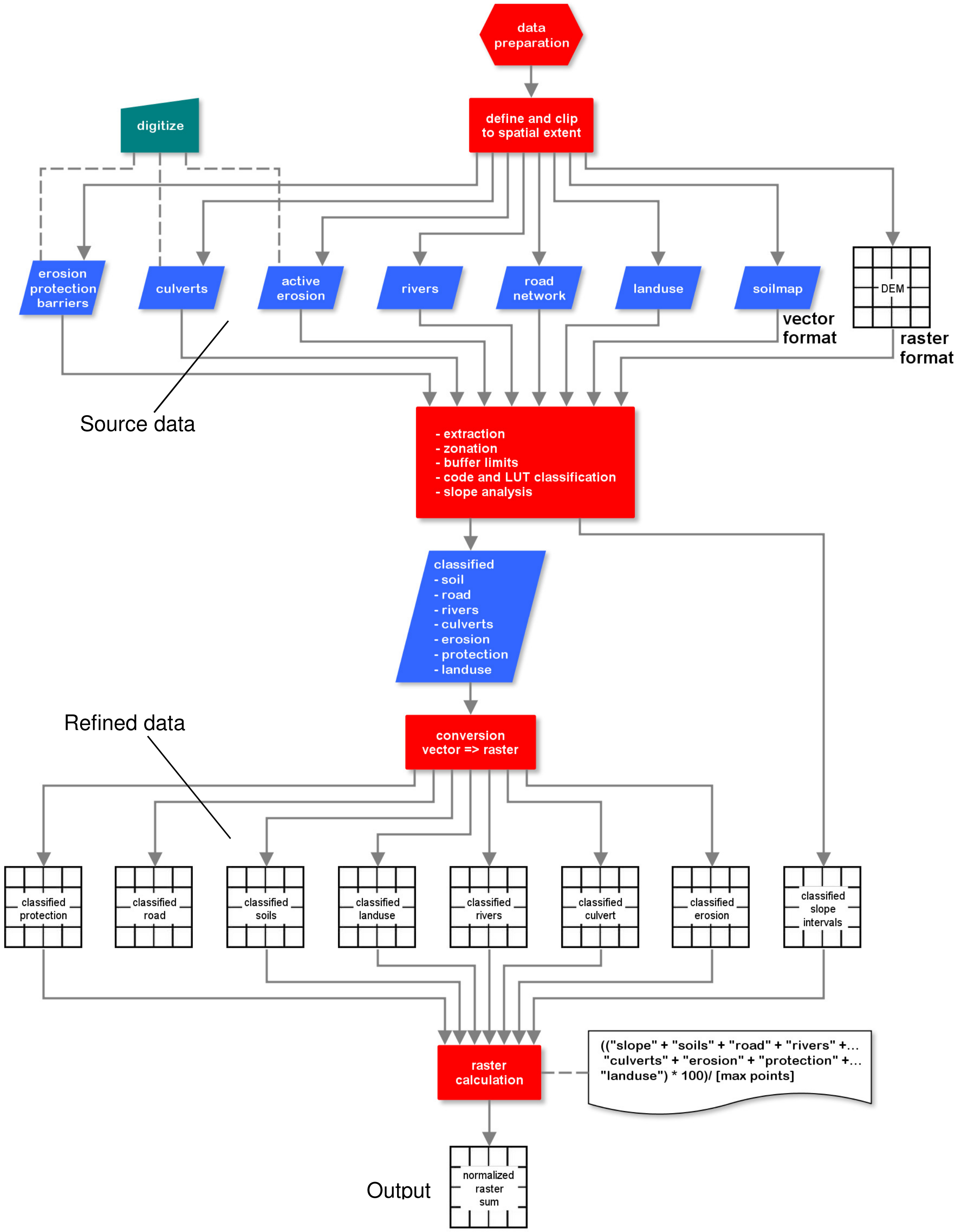


Figure 5. Conceptual flowchart of the GIS processing steps to obtain the Erosion Vulnerability Index, EVI. The blue boxes and the grids represents vector- and raster data respectively while the red boxes highlights a set of processes or calculations.

4 Input data for vulnerability assessment

Various GIS datasets are needed as input for the existing vulnerability assessment methods and for the proposed Roadapt VA method. Presently, most detailed GIS datasets are produced on national or regional level. There are GIS datasets covering all of Europe, but generally these datasets are less detailed than the nationally produced datasets.

It can be a challenge to harmonise different national datasets for use in a transnational vulnerability assessment study. The EU INSPIRE directive (DIRECTIVE 2007/2/EC) aims at harmonizing national GIS datasets within EU. INSPIRE provides common themes for presentation of existing GIS data and states that all existing national data covered by the directive must be published in the INSPIRE web-portal formatted according to the themes provided. Thereby the INSPIRE directive will result in harmonized GIS datasets for widely different fields and the issue of data harmonisation will be solved for all input data that is covered by the directive. When fully implemented, national GIS datasets on e.g. road network, digital elevation models, geology, land cover and hydrography will be available in common themes. Note that the INSPIRE directive does not demand that new data should be produced, only harmonisation of existing data.

Existing GIS datasets on transnational scale and INSPIRE GIS data themes have been identified to cover as many vulnerability factors as possible. The results are listed in Annex B.

It is recommended to use existing GIS datasets in the following priority:

- For transnational scale vulnerability assessment:
  1) INSPIRE GIS datasets
  2) Transnational scale GIS datasets
  3) National scale GIS datasets for the studied countries
- For regional/national scale vulnerability assessment:
  1) Regional/national scale GIS datasets
  2) INSPIRE GIS datasets
  3) Transnational scale GIS datasets

5 Conclusions

The literature study of existing vulnerability assessment methods that are GIS compatible (Annex C) show that GIS-aided vulnerability assessment methods are missing for a large part of the climate change-related threats that the TEN-T network is facing. The existing methods cover the following threats:

- Slides of the road embankment
- External slides, ground subsidence or collapse, affecting the road
- Snow avalanches
- Rock fall
- Debris flow
- Pluvial flooding
- Flooding due to failure of flood defense system of rivers and canals
- Erosion of road embankments
- Cracking due to weakening of the road base by thaw
- Reduced ice removal planability
- Reduced snow removal planability
- Icing and snow

A draft version of a new vulnerability assessment method, Roadapt VA, was outlined in this project. The Roadapt VA method provides the basis for vulnerability index calculation for all threats that are mentioned in the *Climate change induced threats* table (Annex A, Table A.2). Using Roadapt VA it is possible to assess vulnerability to threats without having information on probabilities of occurrence. The method is possible to use together with the RIMAROCC Framework by substituting some of the RIMAROCC sub-steps. The output of the vulnerability analysis is spatially distributed vulnerability index scores in the form of a GIS dataset. Therefore the vulnerability map is easy to use together with additional GIS data. For Roadapt VA to be ready-to-use the method should be tested in case studies. When a new vulnerability scoring table is created it should be tested and evaluated.

Sets of vulnerability factors for each threat are provided in Annex A, and were identified through existing vulnerability assessment projects and through expert knowledge.

Roadapt VA demands that vulnerability scoring tables are developed specifically for each threat to provide guidance when scoring the vulnerability factors on the proposed 0, +1, +2 scale. The procedure for doing so is described in the method. However for Roadapt VA to be accessible for a wider public, the method should be complemented with ready-to-use vulnerability scoring tables for all climate-change-related risks.

The results of the inventory on GIS datasets for mapping the vulnerability factors show that many contextual site factors are available on an international scale, while most infrastructure intrinsic factors seem to be available only on road-owner scale or on national scale. Some vulnerability factors are not at all available as GIS datasets. In these cases e.g. field inspections, desktop studies or maintenance contractor knowledge is needed to assess and spatially distribute vulnerability scores for different parts of the studied road network, before the data can be digitalized and implemented in the vulnerability assessment.

In 2020, when the INSPIRE directive is fully implemented, nationally produced GIS datasets for a range of vulnerability factors will be available in themes that are common to all EU member states. A recommendation on priorities of data sources for transnational and regional/national scale studies is provided in this report.

The objective to provide a guide on how to put together two different datasets at country borders has been met through the Roadapt VA method since international GIS datasets are provided. By translating each vulnerability factor into a vulnerability score, it is also possible to use two datasets that are not harmonised in a transnational analysis. This requires a simple vulnerability ranking procedure.

Data recorded by road owners themselves constitute a major gap in transnationally harmonised GIS data. It is therefore recommended to start a process for international harmonisation of data from national road databases covering the infrastructure intrinsic factors listed in Annex A. Factors that are used for vulnerability assessment of many different threats should be prioritised. Priority should also be given to infrastructure-intrinsic factors that are used in vulnerability assessment of the threats that are most wide-spread in the TEN-T network.

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- Deltares: Thomas Bles (coordinator and work package leader), Arjan Venmans (work package leader), Mike Woning (case leader) and Niels Eernink
- SGI: Per Danielsson (work package leader), Stefan Falemo (case leader, hired from ÅF), Hjördis Löfroth and Linda Blied
- Egis: Martial Chevreuil (work package leader), Yves Ennesser (case leader), Eric Jeannière, Olivier Franchomme and Lise Foucher
- KNMI: Janette Bessembinder (work package leader) and Alexander Bakker

7 References

Bles, T, Ennesser, Y, Fadeuilhe, JJ, Falemo, S, Lind, B, Mens, M, Ray, M and Sandersen, F (2010). Risk management for roads in a changing climate. A guidebook to the RIMAROCC method. Final version.
http://www.swedgeo.se/upload/FoU/Rimarocc%20Handbook%20complete%2020100930%20final%20version_corrected%201.0.pdf

Annex A: Vulnerability factors

Proposed vulnerability factors for a wide range of climate-change related threats are summarised in Table A1 and Table A2. In Table A1 vulnerability scores are suggested based on RIMAROCC. In Table A2 hints are given on how different factors influence vulnerability, but no scores are suggested. The procedure to score vulnerability factors is described in Roadapt VA sub-step 3.1.

Table A.1: Vulnerability factors that may affect vulnerabilities for all threats, and proposed vulnerability scores.

Vulnerability factor	**Vulnerability score**		
	0	+1	+2
Speed of occurrence / forecast time to event	> 3 days accurate predictions possible	½ to 3 days accurate predictions possible	< 12 hours accurate predictions possible
Level of knowledge of the hazard and its related consequences	Detailed forecasts of occurrence and consequence of hazard	Rough forecasts of occurrence and consequence of hazard	Only qualitative insight (trends), or no idea
Amount and type of information to road users	Matrix boards available	Radio coverage - good to partial	No road information
Age of the infrastructure	< 10 years	10 - 60 years	> 60 years
Design standards for affected structure	Recent design standards (< 10 years)	10 - 50 years	> 50 years or unknown standards
Control and maintenance procedures	Systematic inspection after each unusual climate event + high maintenance means	Periodical inspection (at least 1/year) + average maintenance means	Occasional inspection (only after occurrence of damage) + low maintenance means
Traffic level	< 2 000 veh./day	2 000 - 20 000 veh./day	> 20 000 veh./day

Table A.2: Climate-related threats and sub-threats and the vulnerability factors (contextual site factors and infrastructure-intrinsic factors) that affect vulnerability to roads for each sub-threat.

Main threat	**Sub-threat**	**Infrastructure intrinsic factors = road factors that contribute to vulnerability**	**Contextual site factors = surrounding factors that contribute to vulnerability**
Flooding of road surface (assuming no traffic is possible)	flooding due to failure of flood defence system of rivers and canals	Road surface level (lower = higher vulnerability)	Rivers and canals with flood defence systems (prerequisite)
			Water depths from flooding scenarios
	pluvial flooding (overland flow after precipitation, increase of groundwater levels, increase of aquifer hydraulic heads)	Distribution and hydraulic capacity of culverts, drums, ditches (return period for design rainfall event: shorter return period = higher vulnerability)	Topography (depressions = vulnerable)
			hydrography (proximity to brooks, talwegs = higher vulnerability)
			catchment areas (larger = higher vulnerability)
	Inundation of roads in coastal areas, combining the effects of sea level rise and storm surges	Road surface level (lower = higher vulnerability)	Topography (low-lying areas = prerequisite)
			hydrography (proximity to coastal areas = prerequisite)
	Flooding from snow melt (overland flow after snow melt)	Distribution and hydraulic capacity of culverts, drums, ditches (return period for design rainfall event: shorter return period = higher vulnerability)	Topography (depressions = vulnerable)
			Catchment areas (larger = higher vulnerability)
Erosion of road embankments and foundations	Overloading of hydraulic systems crossing the road	Distribution and hydraulic capacity of culverts, drums, ditches (return period for design rainfall event: shorter return period = higher vulnerability)	Hydrography (proximity to brooks/talwegs = higher vulnerability)
		Maintenance frequency for culverts, drums, ditches (less frequent = higher vulnerability)	Catchment areas (relate to drainage capacity)
			Geology (more erosive material = higher vulnerability)
	Erosion of road bases and road embankments	Drums/culverts (higher vulnerability where drums/culverts cross the road)	Hydrography (proximity to coastline/river/brook/talweg: smaller vertical distance = higher vulnerability)
		Distribution of erosion protection works	Vegetation (less vegetation = higher vulnerability
		Geology of road base/embankment and/or surrounding soil (more erosive material = higher vulnerability)	Observed erosion (observed erosion = higher vulnerability)
		Topography of road base/embankment (higher/steeper slope= higher vulnerability)	
		Maintenance frequency (less frequent = higher vulnerability)	
	Bridge scour	Bridge/pier/abutment (prerequisite)	Hydrography (proximity to river/sea = prerequisite)
		Distribution of scour protection works	
		Maintenance frequency (less frequent = higher vulnerability)	

Main threat	Sub-threat	Infrastructure intrinsic factors = road factors that contribute to vulnerability	Contextual site factors = surrounding factors that contribute to vulnerability
Landslips, avalanches, ground subsidence or collapse	External slides, ground subsidence or collapse affecting the road		Geology (clay/silt = higher vulnerability)
			Topography (larger slope angle = higher vulnerability)
			Underground cavities (exisiting = higher vulnerability)
			Loads (e.g. buildings, depots: higher load = higher vulnerability)
			Observed erosion (observed erosion = higher vulnerability)
	Slides of the road embankment	Embankment geology (clay/silt = higher vulnerability)	Hydrography (proximity to brooks/talwegs = higher vulnerability)
		Embankment topography (higher slope angle = higher vulnerability),	
		Observed erosion (observed erosion= higher vulnerability)	
		Distribution of erosion protection works	
		Ground imporvement works (higher vulnerability if not compliant with current design standards)	
		Maintenance frequency (less frequent = higher vulnerability)	
	Debris flow	Road base material (finer material = higher vulnerability)	Vegetation (decrease in vegetation = higher vulnerability)
		Embankment vegetation (less vegetation = higher vulnerability)	Geology (prone to debris flow = higher vulnereability)
		Distribution of erosion protection works	Topography (larger slope angle = higher vulnerability)
			Observed erosion (observed erosion = higher vulnerability)
	Rock fall	Manmade cracks: road cut/blasting (more cracks = higher vulnerability)	Geology (rock/moraine = prerequisite)
		Rockmass quality in road cut (lower quality = higher vulnerability)	Topography (larger slope angle and height = higher vulnerability)
		Topography of road cut (larger slope angle and height = higher vulnerability)	
		Distribution of rock fall protection works	
	Snow avalanches	Distribution of avalanche protection works	Avalanche tracks (map of possible tracks if available)
			Topography (larger slope angle and higher height = higher vulnerability)
			Vegetation (less vegetation = higher vulnerability)
			Terrain roughness (less rough = higher vulnerability)
			Sun exposure (more exposed = higher vulnerability)

Main threat	Sub-threat	Infrastructure intrinsic factors = road factors that contribute to vulnerability	Contextual site factors = surrounding factors that contribute to vulnerability
Loss of road structure integrity	Impact on soil moisture levels, affecting the structural integrity of roads, bridges and tunnels	Tunnel/trough/low-lying road section (prerequisite)	Topography (depressions = higher vulnerability)
		Detailed design information (vertical distance between the base level of the object and groundwater/surface water level)	Groundwater level (higher = higher vulnerability)
			Surface water level (higher = higher vulnerability)
		Capacity of drainage systems	
		Maintenance frequency of drainage systems (less frequent = higher vulnerability)	
	Weakening of the road base by standing water or watertable rise	See assessment of main threat: Flooding of road surface.	See assessment of main threat: Flooding of road surface.
	(Unequal) settlements of roads by consolidation	Compressible embankment material, heterogeneity (higher compressibility or heterogeneity = higher vulnerability)	Geology (clay/silt/peat = prerequisite, deeper layer = higher vulnerability)
			Load (higher difference in load = higher vulnerability)
			Heterogeneity in geology or ground water conditions (higher heterogeneity = higher vulnerability)
	Instability / subsidence of roads by thawing of permafrost	Depth to permafrost active zone (shallow = higher vulnerability)	Permafrost distribution
			Sun exposure (exposed = higher vulnerability)
	Uplift of tunnels or light weight construction materials by increasing watertable levels	Tunnel/trough/lightweight construction	Topography (depressions/low-lying
		Detailed design information (vertical distance between the base level of the	Groundwater level (higher = higher vulnerability)
		Capacity of drainage systems, maintenance frequency (less frequent = higher vulnerability)	Surface water level (higher = higher vulnerability)
Loss of pavement integrity	Cracking, rutting, embrittlement	Pavement type (concrete = not vulnerable; porous bituminous = less vulnerable; non-porous bituminous = more vulnerable)	Sun exposure (exposed = higher vulnerability)
		Design temperature of the asphalt mixture (lower design temperature = higher vulnerability)	Axle load (higher load = higher vulnerability)
		Porosity of the asphalt mixture (greater porosity = higher vulnerability)	Use of studded tyres
		Pavement age (older = higher vulnerability)	
		Bitumen film thickness (thinner = higher vulnerability)	
		Maintenance records (observed cracks = higher vulnerability)	
	Frost heave	Detailed design information (geology of road base within frost penetration depth)	Geology (Clay, silt, clayey sand, glacial till = higher vulnerability), frost penetration depth (deeper = higher vulnerability), ground water level (higher = higher vulnerbility)
	Aggregate loss and detachment of pavement layers	Pavement age (older = higher vulnerability)	
		Distribution of discontinuities (e.g. seams, cracks: more discontinuities = higher vulnerability)	
	Cracking due to weakening of the road base by thaw	Pavement type (concrete = not vulnerable; porous bituminous = less	Traffic load (higher load = higher vulnerability)
	Thermal expansion of pavements	Pavement type (jointed concrete pavements = prerequisite)	Traffic load (higher load = higher vulnerability)
		Observed cracking along edges of transversal joints	
		Roughness of the longitudinal profile (rougher = higher vulnerability)	
	Decreased utility of (unimproved) roads that rely on frozen ground	Pavement type (unimproved = prerequisite)	Traffic load (higher load = higher vulnerability)

Main threat	**Sub-threat**	**Infrastructure intrinsic factors = road factors that contribute to vulnerability**	**Contextual site factors = surrounding factors that contribute to vulnerability**
Loss of driving ability due to extreme weather events	Reduced visibility		Topography (low-lying areas = more vulnerable)
			Vegetation (field/wetland/grassland = higher vulnerability; forest =lower vulnerability)
			Proximity to sea/lake/river/canal (close = higher vulnerability)
	Reduced visibility during snowfall, heavy rain including splash and spray	Pavement type (porous pavements = less vulnerable to splash/spray)	
		Pavement width (wider = higher vulnerability to splash/spray)	
		Pavement transverse slope angle (lower slope angle = more vulnerable to splash/spray)	
	Reduced vehicle control		Vegetation (forest = less vulnerable)
	Decrease in skid resistance on pavements from slight rain after a dry period		Geology (low cohesion soil = higher vulnerability)
			Land use (agriculture/urban/wasteland = higher vulnerability)
			Vegetation (less vegetation = higher vulnerability)
	Aquaplaning in ruts due to precipitation on the road, splash and spray	Pavement type (concrete = not vulnerable; porous bituminous = less vulnerable; non-porous bituminous = more vulnerable)	
		Existence of ruts/tracks (prerequisite)	
	Decrease in skid resistance on pavements from migration of liquid bitumen	Pavement type (bituminous = prerequisite)	Sun exposure (exposed = higher vulnerability)
		Binder viscosity in asphalt mixture	Traffic load (higher load = higher
	Icing and snow	Bridge (more vulnerable to icing)	Use of winter/studded tyres
		Distribution of snow fences	Vegetation (open areas = higher vulnerability to snowdrift)
Reduced ability for maintenance	Reduced snow removal planability	availability of snow removal equipment as compared to the peak need.	
	Reduced ice removal planability	availability of ice removal equipment and de-icing agent as compared to the peak need	
	Impact on road works: decreased time window for paving	Design temperature of the asphalt mixture (lower design temperature = higher vulnerability)	Sun exposure (exposed = higher vulnerability)
Susceptibility to wildfires that threaten the transportation infrastructure directly		Vegetation on road side (trees/grass = higher vulnreability)	Vegetation/land use (forest = high vulnerability)
Damage to signs, lighting fixtures, supports, pulons, canopies, noise barriers because of strong winds		Distribution and design windspeed of signs, lighting fixtures, supports, pulons, canopies, noise barriers	Vegetation (forest = lower vulnerability)
Trees falling on the road		Vegetation on road side (trees = more vulnerable)	Vegetation (forest/trees = prerequisite)
			Proximity of trees to road (prerequisite)

Annex B: GIS data sources

An inventory was conducted to identify transnational and harmonised national GIS datasets covering as many vulnerability factors as possible. Identified GIS datasets with Europe/world coverage that could fulfil the needs of existing vulnerability assessment methods and the proposed ROADAPT VA are listed in Table B.1. Desirable but not available open source datasets for some vulnerability factors are also listed.

An alternative approach for transnational vulnerability assessment is to use harmonised GIS datasets according to the INSPIRE directive. The themes that are covered by the directive are listed in Figure B.1, and relevant INSPIRE themes are listed in Table B.2. According to INSPIRE's time schedule, existing GIS data related to the INSPIRE themes in all three annexes should be available for WMS services and for download since 2013, in its existing state. Restructured harmonised data should be available by 2017 (Annex I) and 2019 (Annex II and III).

Transnational/harmonised GIS datasets are missing for a number of vulnerability factors. Guidance on how to proceed with these factors is provided in Roadapt VA sub-step 2.2.

Table B.1: Available GIS data sources for transnational vulnerability assessment. Desired information is stated in columns 1-2. Datasets are described in columns 3-8.

Vulnerability factor	Information	Name of GIS-layer	Type	Scale	Coordinate reference system	Owner or processor	Link
Topography: digital terrain model/ digital elevation model DTM/DEM	Elevation	EU-DEM	Raster	ca 25 m/pixel	EPSG:4258	Directorate-General Enterprise and Industry (DG-ENTR), European Commission (EC)	http://www.eea.europa.eu/data-and-maps/data/eu-dem
Topography: slope angle	Slope	EU-DEM Slope	Raster	ca 25 m/pixel		European Environment Agency (EEA)	http://epp.eurostat.ec.europa.eu/portal/page/portal/gisco_Geographical_information_maps/geodata/digital_elevation_model/eu_dem_slope
Topography: aspect	Aspect	EU-DEM Aspect	Raster	ca 25 m/pixel		European Environment Agency (EEA)	http://epp.eurostat.ec.europa.eu/portal/page/portal/gisco_Geographical_information_maps/geodata/digital_elevation_model/eu_dem_aspect
Hydrology: sea level rise	Sea level rise	Hydrodynamics and Sea level rise	Point data		EPSG:4258	Directorate-General for Environment (DG ENV)	http://www.eea.europa.eu/data-and-maps/data/hydrodynamics-and-sea-level-rise
Geology: coastal erosion patterns	Geomorphology, geology, erosion trends and coastal defence works	Geomorphology, Geology, Erosion trends and Coastal defence works	Vector data	1:100 000	EPSG:4258	Directorate-General for Environment (DG ENV)	http://www.eea.europa.eu/data-and-maps/data/geomorphology-geology-erosion-trends-and-coastal-defence-works
Geography: coast line	Coastline	EEA coastline for analysis	Vector data	1:100 000	EPSG:3035	European Environment Agency (EEA)	http://www.eea.europa.eu/data-and-maps/data/eea-coastline-for-analysis
Geography: land use	Landuse	Corine Land Cover 2006 seamless vector data	Vector data		EPSG:3035	European Environment Agency (EEA)	http://www.eea.europa.eu/data-and-maps/data/clc-2006-vector-data-version-2
ground water level	Groundwater (Western Europe)	Digital dataset of European Groundwater Resources	Vector data	1:500 000		European Commission - Joint Research Centre	http://eusoils.jrc.ec.europa.eu/ESDB_Archive/groundwater/overview.html
Geology (rock)	Bedrock (Norway, Finland, UK, Ireland, Austria, Luxemburg)	1GE - 1M:M Harmonized Geological Map		1:1 000 000	WGS84	INSPIRE	http://onegeology-europe.brgm.fr/geoportal/viewer.jsp
Geology (soil)	Soil	ESDB v2 - 1kmx1km Raster Library	Vector data/ raster	1:1 000 000		European soil database (ESDB)	http://eusoils.jrc.ec.europa.eu/ESDB_Archive/ESDB/
	Soil (mainly Western Europe)	1GE - 1M:M Harmonized Geological Map		1:1 000 000	WGS 84	INSPIRE	http://onegeology-europe.brgm.fr/geoportal/viewer.jsp
Hydrography lines	Hydrography (watersheds, rivers etc)	ECRINS - EEA Hydrographic data set	Vector data	1:250 000	EPSG:3035	European Environment Agency (EEA)	http://www.eea.europa.eu/data-and-maps/data/european-catchments-and-rivers-network
bathymetry	Bathymetry	EMODnet-Bathymetry portal	Raster	300 m/pixel		EMODnet	http://portal.emodnet-bathymetry.eu/depth-average
Permafrost distribution	Permafrost and Ground Ice Conditions	Circum-Arctic Map of Permafrost and Ground Ice Conditions	Vector and derived raster	1:10 000 000		National Snow and Ice Data Center (USA)	http://nsidc.org/data/docs/fgdc/ggd318_map_circumarctic/
Traffic load	Traffic load (E-roads)	Traffic census				UNECE	http://www.unece.org/transport/areas-of-work/transport-statistics/statistics-and-data-online/e-roads/transmainwp6e-roads-census-2010.html

Datasets that are desirable but not available are layers showing avalanche tracks, vegetation tracks, terrain roughness, observed erosion, sun exposure, frost penetration depth, vechicle speed, road surface angle, road embankment, road side vegetation and road pavement width.

Annex I

1 Coordinate reference systems
2 Geographical grid systems
3 Geographical names
4 Administrative units
5 Addresses
6 Cadastral parcels
7 Transport networks
8 Hydrography
9 Protected sites

Annex II

1 Elevation
2 Land cover
3 Orthoimagery
4 Geology

Annex III

1 Statistical units
2 Buildings
3 Soil
4 Land use
5 Human health and safety
6 Utility and governmental services
7 Environmental monitoring Facilities
8 Production and industrial facilities
9 Agricultural and aquaculture facilities
10 Population distribution and demography
11 Area management / restriction / regulation zones & reporting units
12 Natural risk zones
13 Atmospheric conditions
14 Meteorological geographical features
15 Oceanographic geographical features
16 Sea regions
17 Bio-geographical regions
18 Habitats and biotopes
19 Species distribution
20 Energy Resources
21 Mineral Resources

Figure B.1: GIS data themes covered by the INSPIRE directive.

Table B.2: INSPIRE GIS data sources for transnational vulnerability assessment, numbered according to Figure B.1.

Vulnerability factor	INSPIRE Theme annex.number	Type (raster/vector)	Scale	Coordinate reference system
Topography: digital terrain model/digital elevation model DTM/DEM	II.1 Elevation	raster	Not specified/ required in INSPIRE	at least ETRS89 is required
Topography: slope angle	Can be derived from II.1 Elevation	raster	- " -	- " -
Topography: aspect	Can be derived from II.1 Elevation	raster	- " -	- " -
Hydrology: sea level rise	Possibly III.14 Metrological Geographical Features	vector	- " -	- " -
Geology: coastal erosion patterns	May be in III.12 Natural Risk zones	vector	- " -	- " -
Geography: coast line	II.8 Hydrography	vector	- " -	- " -
Geography: land use	II.2 Land Cover *	vector	- " -	- " -
ground water level	II.4 Geology	vector	- " -	- " -
Geology (rock)	II.4 Geology	vector	- " -	- " -
Geology (soil)	II.4 Geology + possibly III.3 Soil	vector	- " -	- " -
Hydrography lines	II.8 Hydrography	vector	- " -	- " -
bathymetry	II.1 Elevation	raster	- " -	- " -
Permafrost distribution	Possibly II.2, II.4, III.3	vector	- " -	- " -
Traffic load	I.7 Transport Network	vector	- " -	- " -
Avalanche tracks (map of possible tracks if available)	Can be derived from II.1 + II.4		- " -	- " -
Vegetation change: deforestation/clear cutting	Possibly II.2 Land Cover + can be derived from II.3 Ortoimagery	vector	- " -	- " -
terrain roughness	Can be derived from II.1 Elevation	raster	- " -	- " -
Geology: soil, prone to erosion	Can be derived from II.4 Geology + III.3 Soil	vector	- " -	- " -
observed erosion	May be in III.12 Natural Risk zones + Can be derived from II.3 Ortoimagery	vector	- " -	- " -
sun exposure	Can be derived from II.1 Elevation	raster	- " -	- " -
frost penetration depth				
vehicle speed	I.7 Transport Network	vector	- " -	- " -
Road surface level (lower = higher vulnerability)	II.1 Elevation	vector	- " -	- " -
Road embankment / road side vegetation	Possibly II.1 Land cover. Can be derived from II.3 Ortoimagery	vector	- " -	- " -
Road pavement width	I.7 Transport Network	vector	- " -	- " -
	* Theme III.4 Land Use is functional/socioeconomically related, so it is recommended to use II.2 Land cover.			

ROADAPT - Roads for today, adapted for tomorrow

Guideline - Part C: Performing a GIS-aided vulnerability assessment for roads

Annex C: Summary of existing GIS-compatible vulnerability assessment methods

The existing vulnerability assessment methods that were identified in ROADAPT are listed below. The search for methods was aimed at GIS-aided vulnerability assessment methods. The table however also includes methods that are not developed as GIS methods, but where GIS can be used to perform the analyses. Most of the listed methods are developed to assess risks in the present climate, but can be used to assess risks in a future climate as well, simply by substituting input data for the present climate with data for a future climate.

Threat main	***Threat sub***	***Method name***	***Originator***	***Output of method***	***Input data***	***Reference/ Link***
Landslips and avalanches	**Slides of the road embankment**	Risk inventory for roads using national DTM and other databases	Swedish Transport Administration/ Metria	Embankments with prerequisites for landslides	Road network	http://www.metria.se/Global/Produkter/02_%20Analyser/Dokument/Rapport_Riskinventering-vid-vag-med_hjalp_av_NNH_och_andra_databaser.pdf
				Height / steepness of road embankment	Road width	
					Digital Elevation Model 2m raster	
					Hydrography lines	
Landslips and avalanches	**External slides affecting the road**	Identification of areas with prerequisites for landslides	Swedish Geotechnical Institute and Geological Survey of Sweden	Areas with prerequisites for landslides	Geological map	
					Digital Elevation Model 2m raster	
Landslips and avalanches	**Snow avalanches**	Landslide risk model for the Norwegian road network	Norwegian Road Administration	Probability score for avalanche hitting road. Risk defined as a combination of consequences and probability.	Slope angle in starting zone (Digital Elevation Model)	http://www.vegvesen.no/_attachment/461775/binary/759450?fast_title=Videreutvikling+av +skredrisikomodell+for+vegnettet+i+Norge.pdf
					Slope angle in avalanche track (DEM)	Statens Vegvesen (2012). Videreutvikling av skredrisikomodell for vegnettet i Norge. Report no SVV69.
					Vegetation in starting zone and avalanche track (Vegetation map)	http://www.vegvesen.no/_attachment/127992/binary/250006?fast_title= Uttesting+ av+ skredrisikomodell.pdf
					Area of starting zone (DEM + expert judgement)	Statens Vegvesen (2010). Utvikling og uttesting av skredrisikomodell for vegnettet i Norge. Report nr 2586.
					Height of starting zone (DEM + expert judgement)	
					Topography in avalanche track (DEM + expert judgement)	
					Barriers in avalanche track (DEM + expert judgement)	

Threat main	*Threat sub*	*Method name*	*Originator*	*Output of method*	*Input data*	*Reference/ Link*
					Nr of days per year with >25cm snow depth	
					Nr of days within the avalanche season with snow >30mm/24h, or >50mm/72h (water eq.)	
					Nr of days within avalanche season with wind >10,2m/s in unfavourable direction (Wind speed and direction distribution from relevant weather stations)	
					Nr of days within avalanche season with rapid temperature rise (below 0° --> >+5°)	
					Sun exposure for avalanche starting zone (aspect from DEM, expert judgement)	
					Cornice forming (yes/no), expert judgement	
Landslips and avalanches	**Rock fall**	Landslide risk model for the Norwegian road network	Norwegian Road Administration	Probability score for rock fall hitting road. Risk is defined as a combination of consequences and probability.	Geology in starting zone (Bedrock geological map, expert judgement)	http://www.vegvesen.no/_attachment/461775/binary/759450?fast_title=Videreutvikling+av+skredrisikomodell+for+vegnettet+i+Norge.pdf
					Slope angle in starting zone and rock fall track (DEM)	Statens Vegvesen (2012). Videreutvikling av skredrisikomodell for vegnettet i Norge. Report no SVV69.
					Topography in rock fall track (DEM + expert judgement)	
					Barriers in rock fall track (DEM , aerial photos+ expert judgement)	http://www.vegvesen.no/_attachment/127992/binary/250006?fast_title= Uttesting+ av+ skredrisikomodell.pdf
					Manmade cracks (road cuts, blasting etc) (Expert judgement)	Statens Vegvesen (2010). Utvikling og uttesting av skredrisikomodell for vegnettet i Norge. Report nr 2586.
					Water pressure in cracks (Amount of precipitation in 5year event)	
					Frost weathering (Nr of days where daily mean temperature crosses zero, or is within +-1°C)	
					Vibrations in root systems (Vegetation map, maximum wind speed with one-year return period)	

Threat main	***Threat sub***	***Method name***	***Originator***	***Output of method***	***Input data***	***Reference/ Link***
					External vibrations (Earthquake 3-4 on Richter scale in the last 50-100 years (yes/no))	
					Temperature/ sun exposure (aspect from DEM, expert judgement)	
Landslips and avalanches	**Debris flow**	Landslide risk model for the Norwegian road network	Norwegian Road Administration	Probability score for debris slide hitting road. Risk is defined as a combination of consequences and probability.	Slope angle in starting zone and debris slide track (DEM)	http://www.vegvesen.no/_attachment/461775/binary/759450?fast_title=Videreutvikling+av+skredrisikomodell+for+vegnettet+i+Norge.pdf
					Soil type in starting zone (Quaternary geology map+ expert judgement)	Statens Vegvesen (2012). Videreutvikling av skredrisikomodell for vegnettet i Norge. Report no SVV69.
					Barriers in debris slide track (DEM , aerial photos+ expert judgement)	http://www.vegvesen.no/_attachment/127992/binary/250006?fast_title= Uttesting+ av+ skredrisikomodell.pdf
					Water supply (Maximum precipitation/24 hours, annual precipitation)	Statens Vegvesen (2010). Utvikling og uttesting av skredrisikomodell for vegnettet i Norge. Report nr 2586.
					Changes in drainage paths (Aerial photo, expert judgement)	
					Human activities (excavation, backfill) (DEM, aerial photo, expert judgement)	
					River erosion (Expert judgement)	
					Soil thawing speed (Quaternary geology map, frost penetration depth, expert judgement)	
Flooding of road surface		Swedish Transport Administration /Metria	Swedish Transport Administration/ Metria		Road network	
					Road width	
					Digital Elevation Model 2m raster	
					Hydrography lines	

Threat main	***Threat sub***	***Method name***	***Originator***	***Output of method***	***Input data***	***Reference/ Link***
Flooding of road surface	**Pluvial flooding (overland flow after precipitation, increase of groundwater levels, increase of aquifer hydraulic heads)**	The Blue Spot Model - Level 1	ERA-Net Road (Danish Road Institute, Swedish National Road and Transport Research Institute)	Blue Spots considering only the geographical situation of the filled depressions in the DTM.	DTM or hydro-adapted DTM	
					Catchment area polygons	
Flooding of road surface	**Pluvial flooding (overland flow after precipitation, increase of groundwater levels, increase of aquifer hydraulic heads)**	The Blue Spot Model - Level 2	ERA-Net Road (Danish Road Institute & Swedish National Road and Transport Research Institute)	Blue Spots for any given precipitation scenario. Calculations include ground infiltration effects.	Blue Spot level 1 results	
					DTM or hydro-adapted DTM	
					Catchment area polygons	
					Morphology data	
					Land use map	
					Local or national metrological data with return periods of precipitation scenarios	
Flooding of road surface	**Pluvial flooding (overland flow after precipitation, increase of groundwater levels, increase of aquifer hydraulic heads)**	The Blue Spot Model - Level 3	ERA-Net Road (Danish Road Institute & Swedish National Road and Transport Research Institute)	Data on depths of given blue spots and the duration of a flood. Present ability to pass a given blue spot. Consequences analysis.	Blue Spot level 2 results	
					Hydro-adapted DTM	
					Road drainage systems	
					Local or national metrological data with return periods of precipitation scenarios	

Threat main	***Threat sub***	***Method name***	***Originator***	***Output of method***	***Input data***	***Reference/ Link***
					Traffic loads, alternative routes etc.	
Flooding of road surface	**Flooding due to failure of flood defense system of rivers and canals**	Dutch blue spot application	Deltares	Map with road sections vulnerable to flooding form failure of flood defense system	DTM	Bles et al (2012). Investigation of the blue spots in the Netherlands National Highway. Network http://publicaties.minienm.nl/download-bijlage/21781/investigation-of-the-blue-spots-in-the-netherlands-national-highway-network.pdf
					Dike ring areas	
					Road network	
					Results of flood simulations	
					Water depths from flood risk maps	
					Polder and levee locations	
Flooding of road surface	**Pluvial flooding (overland flow after precipitation, increase of groundwater levels, increase of aquifer hydraulic heads)**	Dutch blue spot application	Deltares	**Vulnerable location with groundwater depth less than 1 m for present and future climate.**	Groundwater depth map	Bles et al (2012). Investigation of the blue spots in the Netherlands National Highway. Network http://publicaties.minienm.nl/download-bijlage/21781/investigation-of-the-blue-spots-in-the-netherlands-national-highway-network.pdf
					Road elevation	
					Groundwater level observations	
					Climate change scenario for groundwater levels	
					Road design standard	
Erosion of road embankments and foundation	**Erosion of road embankments**	SGI Erosion index along coasts and watercourses	Swedish Geotechnical Institute	Erosion index for areas adjacent to water	Digital Elevation Model 2m raster	
					Soil map	
					Batymetry	
					Present and future water levels	
					Erosion protection distribution	
					Land use/vegetation	
					Hydrography	
					Exposure index	

Threat main	*Threat sub*	*Method name*	*Originator*	*Output of method*	*Input data*	*Reference/ Link*
Loss of pavement integrity	**Cracking due to weakening of the road base by thaw**	IRWIN	ERA-Net Road (Foreca Consulting Ltd, Klimator AB & University of Gothenburg)	IRWIN index 9: Number of events when the surface temperature shifts from +1℃ to -1℃	RWIS data: road surface temperature, precipitation, wind speed (30 min time interval)	
					maintenance data: date, time and location for ploughing or salting event, amount of salt used	
					climate scenario data: temperature, precipitation, wind speed	
Loss of driving ability due to extreme weather events	**Icing and snow**	IRWIN	ERA-Net Road (Foreca Consulting Ltd, Klimator AB & University of Gothenburg)	Expected change in need of salting	RWIS data: road surface temperature, precipitation, wind speed (30 min time interval)	
				Index 7: Number of events when it was or had been raining and the surface temperature was less than 0,5℃ (freezing rain, black ice)	maintenance data: date, time and location for ploughing or salting event, amount of salt used	
				Index 8: Number of events when the surface temperature was between -6℃ and 0℃ during 4 hours and the dew point was larger than the surface temperature (risk of hoar frost)	climate scenario data: temperature, precipitation, wind speed	
				Index 9: Number of events when the surface temperature shifts from +1℃ to -1℃		
Reduced ability for maintenance	**Ice removal costs**	IRWIN	ERA-Net Road (Foreca Consulting Ltd, Klimator AB & University of Gothenburg)	Expected change in need of ice-removal / salting	RWIS data: road surface temperature, precipitation, wind speed (30 min time interval)	
				Index 7: Number of events when it was or had been raining and the surface temperature was less than 0,5℃ (freezing rain, black ice)	maintenance data: date, time and location for ploughing or salting event, amount of salt used	

Threat main	*Threat sub*	*Method name*	*Originator*	*Output of method*	*Input data*	*Reference/ Link*
				Index 8: Number of events when the surface temperature was between -6℃ and 0℃ during 4 hours and the dew point was larger than the surface temperature (risk of hoar frost)	climate scenario data: temperature, precipitation, wind speed	
				Index 9: Number of events when the surface temperature shifts from +1℃ to -1℃		
Loss of driving ability due to extreme weather events	**Icing and snow**	IRWIN	ERA-Net Road (Foreca Consulting Ltd, Klimator AB & University of Gothenburg)	Expected change in need of ploughing	RWIS data: road surface temperature, precipitation, wind speed (30 min time interval)	
				Index 1: Number of events when the amount of snow was more than 1mm during 4 hours, temperature was between -3 to +1℃, wind velocity was between 0-7 m/s	maintenance data: date, time and location for ploughing or salting event, amount of salt used	
				Index 2: Number of events when the amount of snow was more than 1mm during 4 hours, temperature was between -3 to + 1℃, wind velocity was between 7-14 m/s	climate scenario data: temperature, precipitation, wind speed	
				Index 3: Number of events when the amount of snow was more than 1mm during 4 hours, temperature was between -3 to + 1℃, wind velocity was more than 14 m/s		
				Index 4: Number of events when the amount of snow was more than 1mm during 4 hours, temperature was less than -3℃, wind velocity was between 0-7 m/s		
				Index 5: Number of events when the amount of snow was more than 1mm during 4 hours, temperature was less than -3℃, wind velocity was between 7-14 m/s		

Threat main	***Threat sub***	***Method name***	***Originator***	***Output of method***	***Input data***	***Reference/ Link***
				Index 6: Number of events when the amount of snow was more than 1mm during 4 hours, temperature was less than -3℃, wind velocity was more than 14 m/s		
Reduced ability for maintenance	**Snow removal costs**	IRWIN	ERA-Net Road (Foreca Consulting Ltd, Klimator AB & University of Gothenburg)	Expected change in need of ploughing	RWIS data: temperature, precipitation, wind speed (30 min time interval)	
				Index 1: Number of events when the amount of snow was more than 1mm during 4 hours, temperature was between -3 to +1℃, wind velocity was between 0-7 m/s	maintenance data: date, time and location for ploughing or salting event, amount of salt used	
				Index 2: Number of events when the amount of snow was more than 1mm during 4 hours, temperature was between -3 to + 1℃, wind velocity was between 7-14 m/s	climate scenario data: temperature, precipitation, wind speed	
				Index 3: Number of events when the amount of snow was more than 1mm during 4 hours, temperature was between -3 to + 1℃, wind velocity was more than 14 m/s		
				Index 4: Number of events when the amount of snow was more than 1mm during 4 hours, temperature was less than -3℃, wind velocity was between 0-7 m/s		
				Index 5: Number of events when the amount of snow was more than 1mm during 4 hours, temperature was less than -3℃, wind velocity was between 7-14 m/s		
				Index 6: Number of events when the amount of snow was more than 1mm during 4 hours, temperature was less than -3℃, wind velocity was more than 14 m/s		