Technical Notes

Flood Risk in Road Networks

WORLD BANK GROUP
Social, Urban, Rural & Resilience

CAPRA

Funded by:

GFDRR
Global Facility for Disaster Reduction and Recovery

Australian Government
Department of Foreign Affairs and Trade

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BACKGROUND

Road networks are essential for economic, social, environmental, and security reasons. Road networks are therefore considered critical networks according to the consequences of their disruptions (Tacnet and Mermet 2012). Flooding poses an important threat to roads, and can lead to massive obstruction of traffic and damage to road structures, with possible long-term effects (Buren and Buma 2012). Flooding leads to significant repair costs for road control authorities, access difficulties for emergency services (Versini, Gaume, and Andrieu 2010a), and disruption for road users and the community at large. The consequences for businesses and the economy in general can be very significant (Brabhaharan, Wiles, and Frietag 2006). Because of the time and costs required for rebuilding, sustainable and long-term planning is crucial (Michael, Høegh, and Søren 2010); therefore, the consideration of flood risk constitutes an important input for decision making in planning this type of infrastructure. Flood risk analysis for road networks allows plans to be carried out in an appropriate manner, allocating resources for prevention, mitigation, and restoration (Balijepalli and Oppong 2014; Jenelius and Mattsson 2014).

When road networks are disrupted by a hazardous event, the effects can be critical for emergency management. Transportation lifelines are generally considered the most important in an emergency because of their vital role in the restoration of all other lifelines (Cova and Conger 2004). Road network disruptions can threaten the ability to provide medical care and other critical services (Jenelius and Mattsson 2014).

This report summarizes the main concepts and methodologies that are used to assess flood risk for road networks. The report presents references and examples, and is intended to be a starting point for practitioners in the field.

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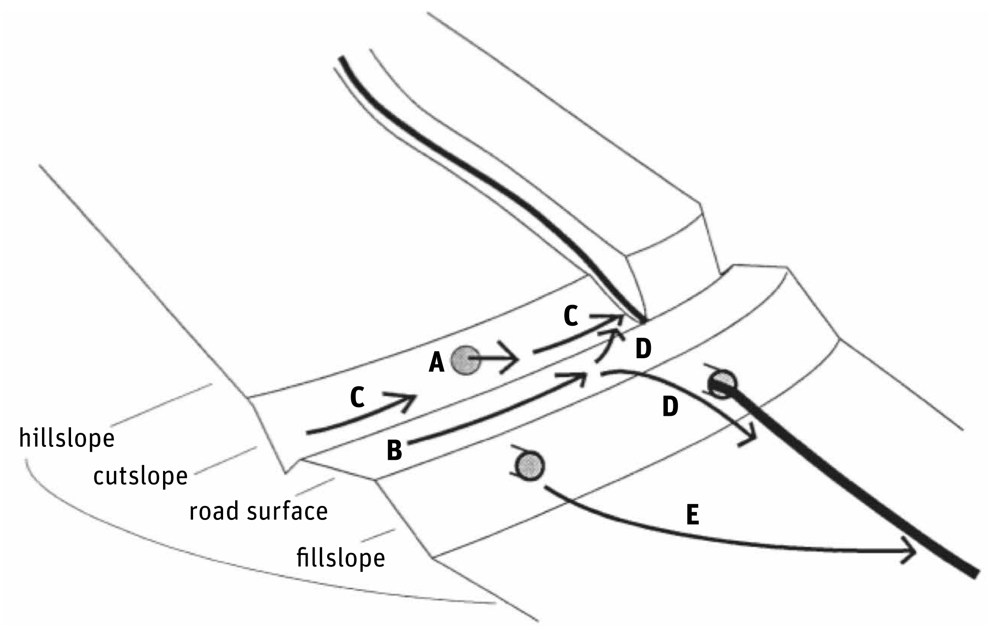
INTERACTIONS BETWEEN ROADS AND FLOODS

Roads can be damaged by floods and also can enhance hazardous flood conditions. The flooding of a road induces two levels of consequences: on the one hand, people may be injured and vehicles may be destroyed; on the other hand, the disruption of traffic may have severe indirect consequences. Road closures can have economic, social, and security consequences (Tacnet and Mermet 2012). At the same time, roads and road development can have considerable effects on natural flood patterns and effects. Roads fragment habitats and interrupt the flow of water, sediments, nutrients, and aquatic life, thereby impacting the beneficial effects of the natural flood cycle (Douven, Goichot, and Verheij 2009).

Road development in floodplains alters the floodplain hydraulics and affects the related aquatic ecosystems (Douven, Goichot, and Verheij 2009). Figure 1 shows the interactions that can occur between road segments and flows of water or sediment. Roads may act as corridors for flows of water on road surfaces (A and B in Figure 1) or in roadside ditches (C in figure 1). And roads may be sources of water for stream networks through culverts (D in figure 1) or gullies (E in figure 1). The interaction between roads and streams may modify the magnitude and direction of flows of water and debris, and water flows may transform into debris flows or vice versa (Jones et al. 2000).

Figure 1 **Types of Water Flow on a Road**



Source: Jones et al. (2000).
Note: The figure shows five types of interactions involving water between a midslope road parallel to contour and a stream (heavy solid line).

The failure of a road network is of concern for road users (passengers and freight), support infrastructure (road, security equipment, bridges, etc.), critical infrastructure supported on elements (such as bridges or tunnels) of the road network (power, telecommunications, etc.), and the transport function (connectivity and accessibility of points connected to each other by the road) (Tacnet and Mermet 2012). Flooding causes traffic disruption, which disappears as soon as the water subsides and goes back into its bed. In some cases, after a flood, there is a layer of silt, such as mud or other coarse-grained material. In mountainous areas or where there is a sufficient bottom slope, the water has enough energy to produce partial or complete destruction (Bil et al. 2014).

The types of flooding in a road network can be divided into three groups (Michael, Høegh, and Søren 2010):

- If there is insufficient capacity in the drainage system, water on the surface collects in depressions in low-lying areas. The contributing drainage areas can be the surrounding areas as well as direct drainage on the road.
- Rivers may flood because there is insufficient downstream capacity.
- Rising sea level causes flooding of low-lying areas.

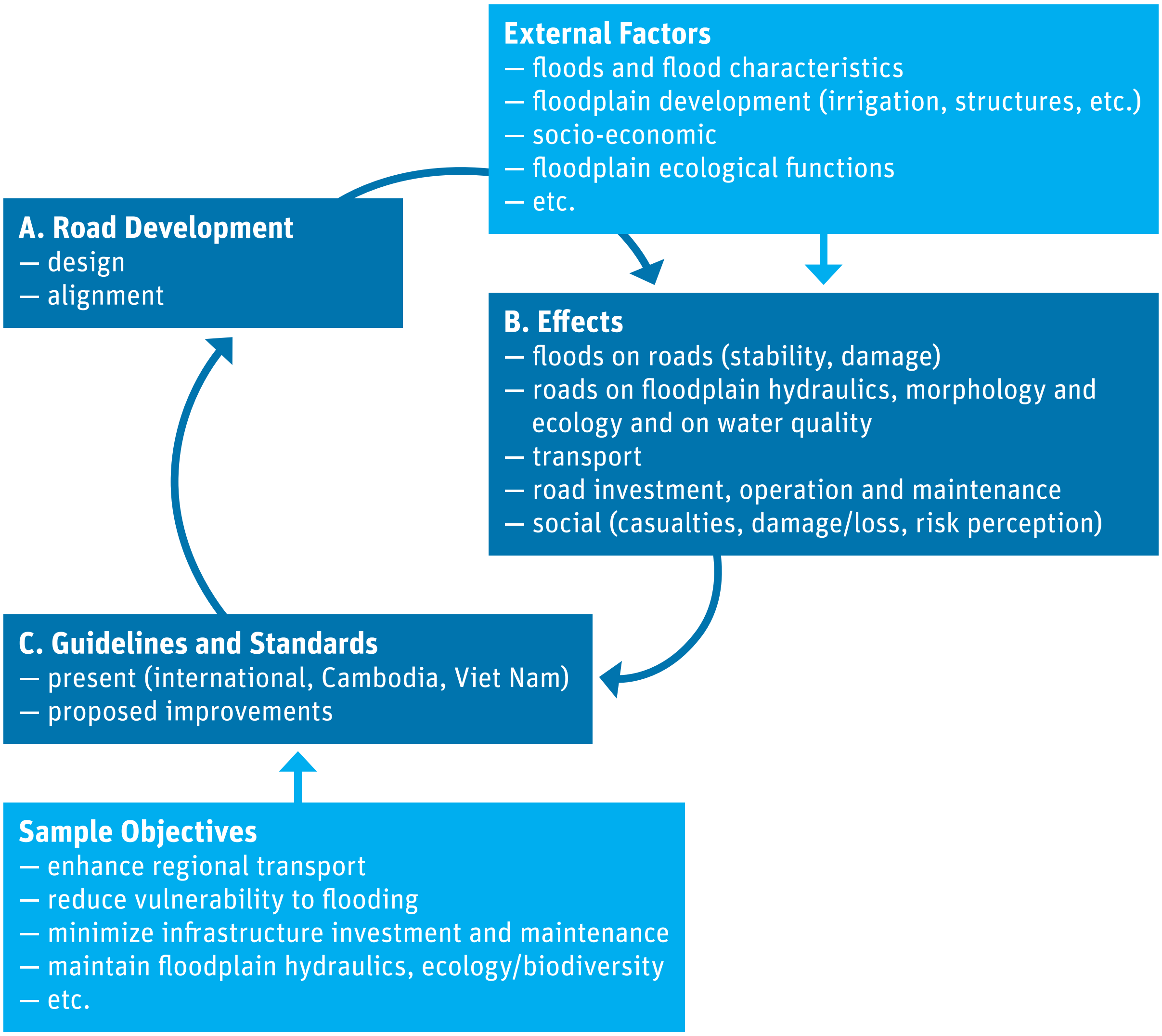
Flooding in a road network can have the following effects (Buren and Buma 2012):

- Water that collects on the road because of the failure of flood defenses leads to traffic stagnation or, if the water reaches a certain depth, traffic stoppage. High water levels on the road or on the sides of the road construction can lead to loss of bearing capacity for the short and long term after flooding. Deep-lying sections, tunnels, as well as roads with a lightweight foundation can be prone to uplift and heave.
- Intense rainfall can increase pluvial flooding and instability of the road foundation.
- Excess groundwater levels can cause uplift and heave of roads in excavation, loss of bearing capacity, uplift of roads with a lightweight foundation, and leaching of pollution. Possible effects of excess hydraulic heads, in the aquifer directly below the cover deposits, include uplift and heave of roads.
- The appearance of water on roads during heavy rain can lead to road closures and safety problems for vehicles. During heavy rain, the development of spray behind vehicles results in poor visibility. And in the worst case, water on the road may cause vehicles to aquaplane.

The impacts can be divided into direct and indirect ones. Direct impacts include the costs of reconstruction of damaged roads and the reconstruction of landslide areas or adjustment of erosion entrained banks. Indirect impacts entail the costs of interruption and logistics disruptions. For example, when a portion of the road is closed, the detours are always less favorable because they are longer or more time consuming (Berdica 2002). These extra costs are part of the indirect costs. Other indirect costs can be formulated as lost opportunities if planned trips are not carried out or other modes of transportation are chosen (Bil et al. 2014). The inaccessibility of inundated roads during emergency management activities could cause indirect damage to the operability of strategic structures, such as hospitals and fire stations (Albano et al. 2014).

The integration of road planning and design and flood risk management plays a crucial role in developing efficient and sustainable road networks in floodplains. Figure.2 presents a framework for integrated analysis of road planning and design. The figure shows the relation between road development design and planning (A) and the various effects (B), which are linked to the use of standards and guidelines (C). In road development and planning, all effects should be taken into account through the use of economically sound and environmentally friendly guidelines for the planning and construction of roads in floodplains (C) (Douven, Goichot, and Verheij 2009).

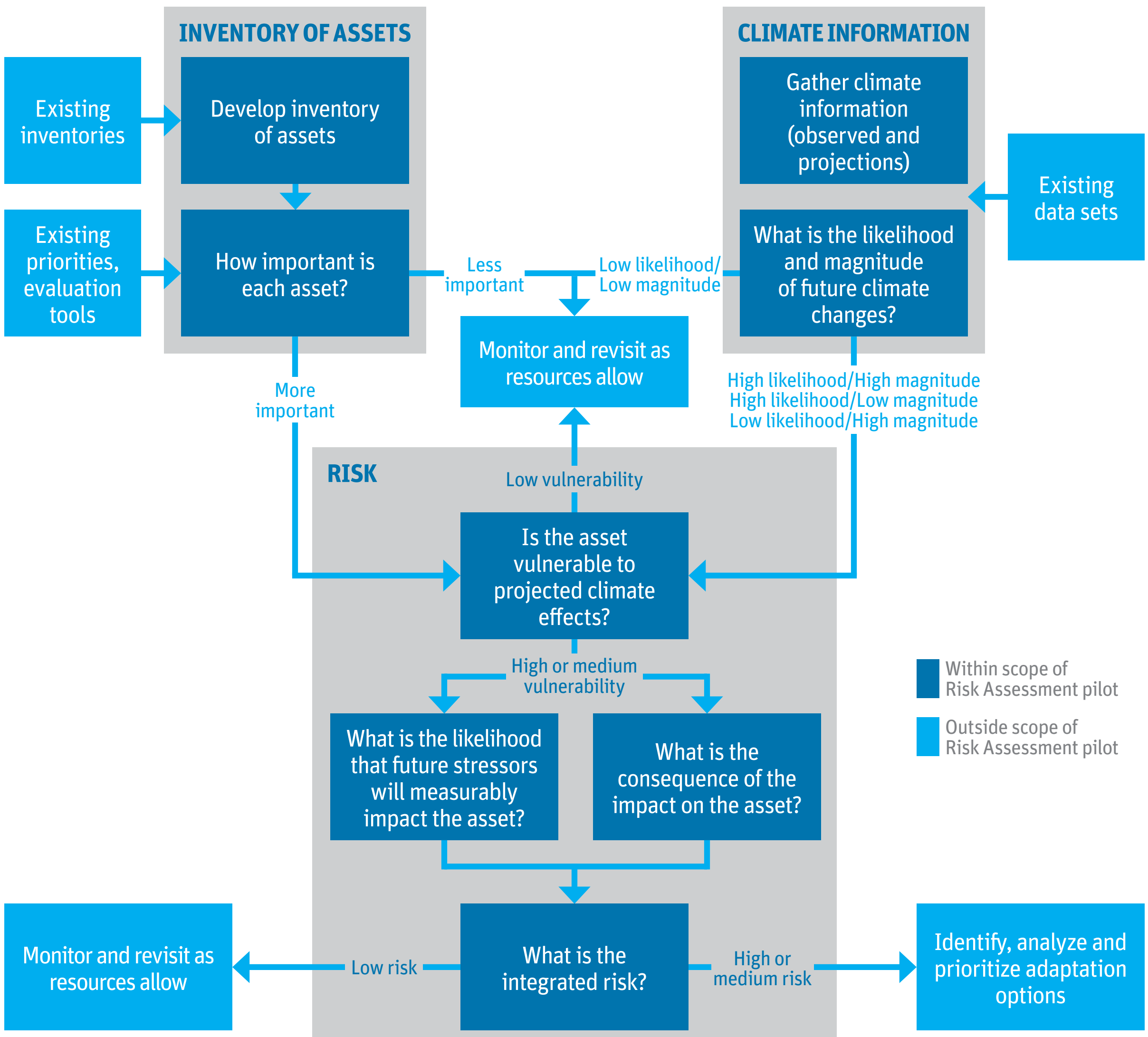
Figure 2 **Conceptual Framework for Road Design and Planning in a Floodplain**



Another relevant aspect in road planning and design is climate change. Taking climate change into consideration requires good flood maps and good planning for water management. In addition, consideration of climate change may have an impact on standard design procedures, since the methods for calculating and estimating the capacity of drainage works may be insufficient (CEDR 2012). A relevant concept is climate proofing, which involves identifying the risks to a development project as a consequence of climate variability and change, and ensuring that those risks are reduced to acceptable levels through environmentally sound, economically viable, and socially acceptable changes (Lal and Thurairajah 2011).

The Federal Highway Administration developed a conceptual model for understanding the ramifications of climate change for transportation infrastructure. The model consists of three interrelated steps. The first step is to develop an inventory of assets and prioritize them based on vulnerability, as shown in the upper left of figure 3. The second step is to combine climate data for a region to understand the specific drivers of vulnerability, as shown in the upper right of figure 3. The third step in the conceptual framework, shown in the center of figure 3, involves quantitative risk analysis to identify the most vulnerable transportation assets (VDOT et al. 2011).

Figure 3 **Structure of the FHWA Conceptual Framework for Risk Assessment and Adaptation of Transportation Infrastructure to Climate Change**



Source: VDOT et al. (2011).

Suarez et al. (2005) provide an example that includes climate change in road network flood risk analysis. Their approach estimates the impacts of flooding on a road network under the influence of climate change. The approach requires a model that is capable of simulating road traffic flows under a variety of conditions. The model is first run under normal circumstances to provide baseline values for traffic volume and travel time. Then a set of flooding scenarios is designed to identify those areas that are flooded, so that no trips begin or end there, and those network links that are disrupted. The model is rerun and the results are compared with the initial run to determine how many lost trips and how much extra travel time may be attributed to the weather event. This type of analysis provides a basis for estimating the transportation-related costs of more frequent and more extreme weather events under various climate change scenarios. To capture the effects of flooding on the performance of the transportation network, different flooding scenarios are defined, based on combinations of the year of simulation (2003 or 2025), area flooded (no flooding, 100-year floodplain, or 500-year floodplain), and type of flooding (coastal, riverine, or both).

VULNERABILITY

In transportation studies, the concept of vulnerability is used to recognize that susceptibility is not uniform across people, vehicles, traffic flow, infrastructure, or the environment. Vulnerability can refer to the physical vulnerability of the transportation users or the potential for an incident to decrease the serviceability of the transportation system. Vulnerability in transportation can also be approached from the point of view of network reliability, as a reliable network is less vulnerable (Cova and Conger 2004) and therefore more resilient when a disaster event occurs.

The impact of the disruption of a given element is called the importance of the element. Many other terms have been used in various fields for the same concept, including "criticality" (Taylor and Susiwalati 2012) and "vulnerability" (Jenelius and Mattsson 2014). The main purpose behind the importance measure is to compare and rank different elements. This allows, for example, the identification of the parts of the transport system where disruptions would be particularly severe. Disruptions of such elements represent worst-case scenarios and the elements can also be considered potential targets for antagonistic attacks on the system. Identifying important elements means that targeted measures can be taken to reduce the risk of disruptions in those locations.

The combination of importance and disruption probability is called the criticality of the element. Importance can thus be expressed as conditional criticality (Jenelius and Mattsson 2014). Another important concept is resilience, which is defined by U.S. Presidential Policy Directive 21 (PPD-21) as "the ability to prepare for and adapt to changing conditions, and withstand and recover rapidly from disruptions." Therefore, analysis of the resilience of a road network should address the physical characteristics of the road network and the activities it supports (World Bank 2015).

The definition of vulnerability has not yet been generally accepted (Susilawati and Taylor 2008). Most concepts of vulnerability are based on reduction in the performance of the road network. Some definitions of vulnerability include the following:

- Road network vulnerability analysis can be defined as the study of potential degradations of the road transport system and their impacts on society through modeling the road infrastructure as a network with links (road segments) and nodes (intersections) (Jenelius and Mattsson 2014).
- The expectance (E) of physical impacts (low, medium, or high[1]) to assets or networks, given different levels of exposure (World Bank 2015).
- *"A susceptibility to incidents that can result in considerable reduction in road network serviceability"* (Berdica 2002). The link, route, or road serviceability describes the possibility to use that link, route, or road during a given period of time. Furthermore, since accessibility depends on the quality of the functioning of the transportation system, this concept has to do with different levels of vulnerability in reducing accessibility for various reasons.
- Taylor, Sekhar, and D'Este (2006) define vulnerability as follows:
  1. A network node is vulnerable if loss (or substantial degradation) of a few links significantly diminishes the accessibility of the node, as measured by a standard index of accessibility.

1. For transport networks, levels of impacts are defined as open with minimum loss of road capacity, partially closed, and fully closed.

2. A network link is critical if loss (or substantial degradation) of the link significantly diminishes the accessibility of the network or particular nodes, as measured by a standard index of accessibility.

This definition implies that road vulnerability assesses the weakness of a road network to incidents and the adverse impacts for the community of degraded road network serviceability.

- Vulnerability is a combination of the potential for damage; the associated costs; and the exposure of persons, goods, infrastructure, and vehicles. This definition of vulnerability relates to the consequences of natural phenomena, and can be decomposed into direct and indirect vulnerability. Direct vulnerability corresponds to physical damage directly linked to the effects of phenomena such as physical injury of people or damage to infrastructure (caused by road rupture, debris flows, avalanches, deposition, rockfalls, etc.). Indirect vulnerability corresponds to the remote consequences of an event, such as a flood, avalanche, or debris flow (Tacnet and Mermet 2012).

In general, defining vulnerability allows identifying structural weaknesses in the network topology that render the network vulnerable to the consequences of failure or degradation. Resources can then be targeted at assessing these weak links (Taylor, Sekhar, and D'Este 2006).

The following subsections present the main methodologies that are used for analysis of road network vulnerability.

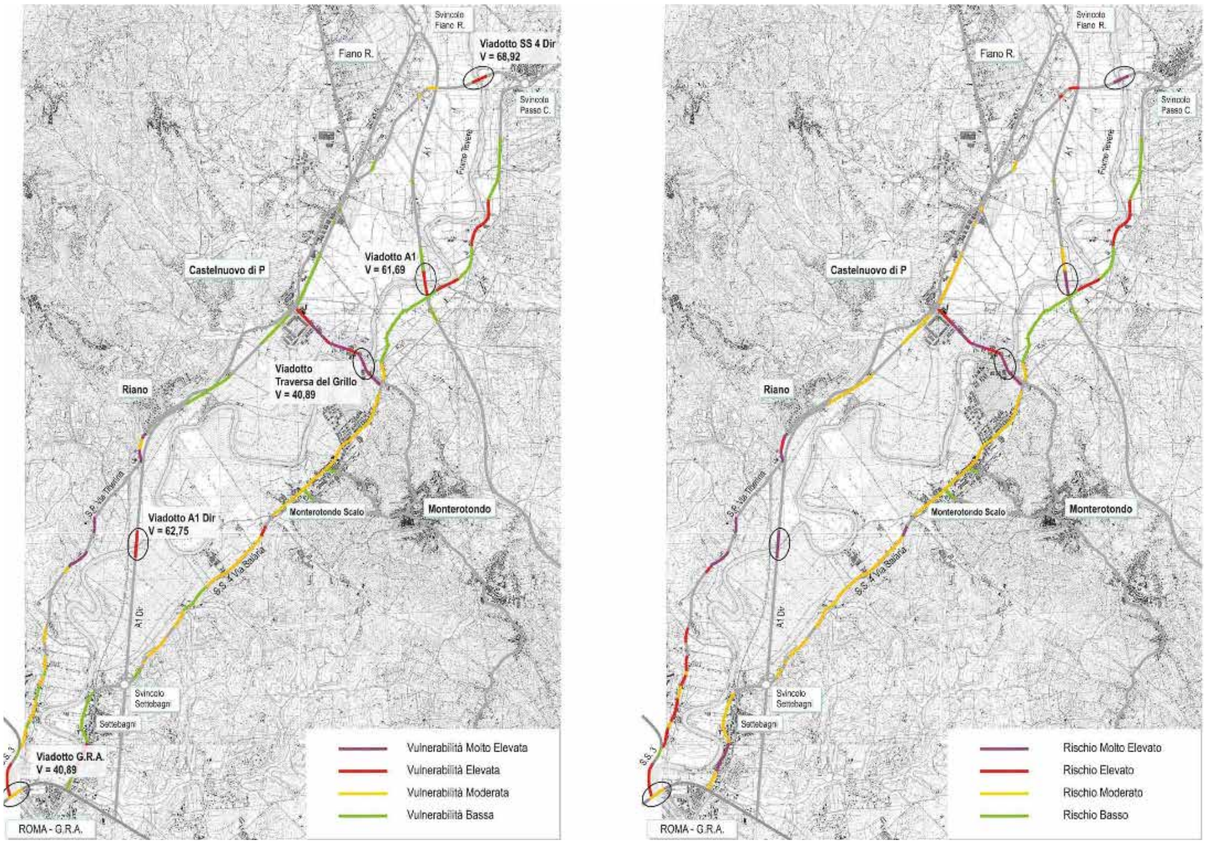
Multi-Criteria Analysis Techniques

Multi-criteria analysis establishes preferences between options. It makes a comparative assessment between alternatives or heterogeneous measures. For example, Benedetto and Chiavari (2010) present an analytical model for road vulnerability assessment based on multi-criteria analysis. For each road element j, vulnerability V_j is determined by:

$$V_j = \sum_{i=1}^{N} Y_i \cdot P_i$$

where P_is are vulnerability parameters and Y_is quantify the effect of each parameter on total vulnerability (they represent the degrees of freedom in this model). The P_i are hydraulic, geotechnical, structural, and functional parameters (sensitivity). A specific parameter set is defined for each typological element (adaptability). Each parameter can assume the value 0, 1, or 2, depending whether the parameter implies low/none, medium, or high vulnerability for the element. Quantitative and qualitative vulnerability parameters are defined. Assignment of values is based on the values assumed by the entity considered for the quantitative parameters, and on qualitative assessment categories for the qualitative parameters. Map 1 shows the results of the analysis applied to the road network in Northern Rome in the Tiber floodplain.

Map 1 Analysis of the Road Network in the Tiber Floodplain in Northern Rome



Source: Benedetto and Chiavari (2010).

The RIMAROCC method (Bles et al. 2010) uses several indicators in applying multi-criteria analysis to risk assessment of roads. The methodology conceptualizes the process of identification of vulnerabilities as looking for the vulnerable elements of the road system in the event of the occurrence of an unwanted (detrimental) event. The study of vulnerabilities in the RIMAROCC methodology includes the following: (i) sensitivity and exposure of an asset (road, right-of-way, equipment, maintenance vehicles, etc.) to risk factors and/or an unwanted event; (ii) traffic; (iii) the age of the infrastructure; (iv) design standards; (v) maintenance practice (routine and heavy repairs); (vi) the adaptability of the asset; and (vii) the possibility of upgrading without complete reconstruction of the asset.

Table 1 shows the vulnerability indicators proposed by the RIMAROCC methodology, which are subsequently used to assess risk in a multi-criteria analysis framework. Estimation of the indicators requires collecting data, such as construction date, standards used, materials, equipment, etc., with the level of precision depending on the scale of the analysis. The estimation also requires data on actual traffic and a comparison with expected traffic for traffic counts, type, origin-destination analysis, etc., as well as data on maintenance (routine and heavy repairs) and structural defects or existing damages that would likely be worsened by climate factors. The main infrastructure components to be investigated are major hydraulics, minor hydraulics and drainage, engineering structures, equipment, geotechnics, environment, and pavement.

Table 1 Vulnerability Indicators Proposed by the RIMAROCC Methodology

	Low (1)	Medium (2)	High (3)	Critical (4)
V1 — Speed of occurrence/forecast time to event	>3 days accurate predictions possible	½ to 3 days accurate predictions possible	<12 hours accurate predictions possible	<5 hours accurate predictions possible
V2 — 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)	No idea
V3 — Amount and type of information to road users	Matrix boards available	Good radio coverage	Partial radio coverage	No road information
V4 — Age of the infrastructure	<10 years	10–30 years	30–100 years	>100 years
V5 — Design standards	Recent design standards (<5 years)	5–25 years	25–50 years	>50 years or unknown standards
V6 — 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 occurence of damage) + low maintenance means	Almost no inspection or maintenance means
V7 — Traffic level	<2,000 vehicles/day	2,000–10,000 vehicles/day	10,000–50,000 vehicles/day	>50,000 vehicles/day
V8 — Site factors likely to worsen climate risks	Optimal situation regarding land cover, topography, erosion and flood control	Acceptable situation regarding land cover, topography, erosion and flood control	Degraded situation regarding at least one site factor	Degraded situation regarding all site factors, or situation highly degraded for one site factor

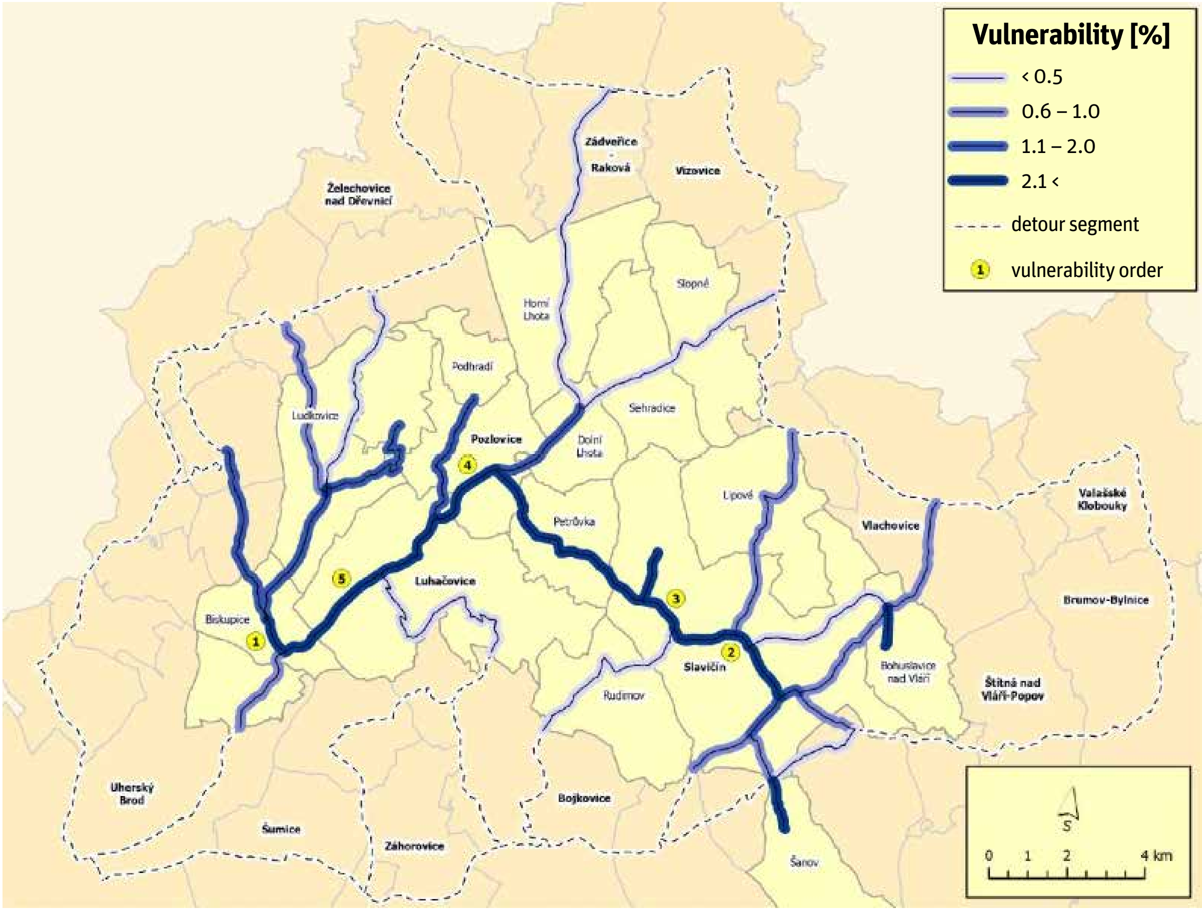
Source: Bles et al. (2010).

Road networks serve different demands or clients and the approaches that have been described are just a snapshot of the possible methods to be used when assessing vulnerability and criticality.

Serviceability Analysis

The serviceability of a link is defined as the possibility of using that link during a given period of time, which then relates to the possibility of the partial degradation of the roads. Finally, if the consequences of a link being affected are great, then the link is considered critical to the network (Balijepalli and Oppong 2014).

Map 2 Vulnerability of a Road Network in Luhacovice, Czech Republic



Source: Bil et al. (2014).

Bil et al. (2014) address vulnerability as the impact of interruption of a specific segment on the serviceability of the whole network (repair costs will be directly proportional to the length of an affected road and will differ according to the types of objects at the location of the interruption; repair costs will be highest in the case of repairs of bridges and tunnels). Map 2 shows the results of the analysis in the Czech Republic. The weakest segments are in the middle part of the territory. If those segments were interrupted, the length of the connection (detour route) between the end nodes would grow substantially.

Another example of the use of the serviceability concept in the vulnerability analysis of roads is the use of the Network Vulnerability Index, which takes into account the serviceability and importance of each road link in the network (Balijepalli and Oppong 2014). The serviceability of link i is calculated by dividing the total available capacity of the link by the standard hourly maximum flow rate (that is, capacity) per lane for a given type of road. The total available capacity of a link is obtained by summing the capacity of all the available operational lanes.

Accessibility Indexes

Accessibility is defined by Susilawati and Taylor (2008) as the ease with which people can participate in activities from a specific location by use of a transport mode. With this definition, accessibility can be used to evaluate the performance of the transport system. Box 1 shows an example, taken form Susilawati and Taylor (2008), of the application of indexes to identify critical links. Several indexes measure accessibility:

- **Hansen index.** The Hansen index considers not only the generalized cost of travel, but also the attractiveness of the location, which represents the size of activity, such as the population, the number of theater seats, the number of jobs, as well as the size of shopping centers. The Hansen integral accessibility index for a location can be written as:

  $$A_i = \sum_i B_j f(C_{ij})$$

  where A_j is the integral accessibility, B is the attractiveness of location (city) j, and C is the number of opportunities available at j. Often B is taken as the population of city j, and $f(C_{ij})$ is the impedance function, which represents the separation between i and j. The impedance function $f(C_{ij})$ in the equation for the index can be the travel time and travel cost. Thus, the higher the impedance function, the lower the accessibility index at the particular area. Taylor, Sekhar, and D'Este (2006) used the reciprocal of the distance between two cities (x_{ij}) as the impedance factor, implying that for a higher cost of travel between the two cities, the accessibility between them is lower.

- **Destination accessibility index.** This index measures the ability of evacuees to access destinations (such as assembly points or evacuation centers). If the failure or capacity degradation of a road section affects maximum reduction in the accessibility index, that road is identified as a critical location (Luathep et al. 2013).

- **Accessibility/Remoteness Index of Australia (ARIA).** ARIA is a remoteness index that measures the distance from populated localities to vital service centers. This index can also be defined as the accessibility of a populated locality center to the various sizes of vital services, such as health, finance, and education.

- **Generalized travel cost.** Given the origin-destination flows, the difference between the least cost path with the network intact and the least cost path without the link being evaluated is estimated. Therefore, overall increases in cost in a degraded network can be assessed (Taylor, Sekhar, and D'Este 2006).

- **Network efficiency measure.** This index corresponds to the average number of trips per unit cost and represents the efficiency of the network by the traffic-to-cost ratio. The higher is the traffic handled per unit cost, the more efficient the network is (Balijepalli and Oppong 2014).

- **Importance measure.** The importance measure assumes that all drivers are forced onto a more expensive route when an event causes the disruption or closure of a link or a group of links. More expensive routes not only refer to economics as a cost function in transport analysis, but also may imply mean travel time and travel distance. The behavior is described by the user equilibrium principle, where the route choice is meant to minimize personal travel cost. The basis for the measure is the change in the cost of travel (Balijepalli and Oppong 2014).

- **Network robustness index.** The network robustness index is defined as the change in travel time cost associated with rerouting all traffic in the system should that segment become unstable. The index is based on the capacities of individual links and considers the rerouting options for the origin-destination pairs that use the link. The index then uses travel time to measure the cost of rerouting traffic should a link be completely removed. The index assumes that the disruption will cause a complete closure of the link and that drivers follow user equilibrium in route choice. The system cost of travel for when all the links are intact is also calculated and the difference is the network robustness index (Balijepalli and Oppong 2014).

HAZARD ANALYSIS

Hazard can be defined as a dangerous phenomenon, substance, human activity, or condition that may cause loss of life, injury, or other health impacts, property damage, loss of livelihoods and services, social and economic disruption, or environmental damage (UNISDR 2009). In the context of road networks, the damage caused by a dangerous phenomenon—in this case, flooding—can include all the impacts addressed in the section on Interactions between Roads and Floods. In contrast, susceptibility describes the likelihood that a road section will be flooded, given the natural hazard. Susceptibility is the frequency of flooding of the considered road section over a long period of time (Versini, Gaume, and Andrieu 2010a).

There are several important dimensions in transportation hazard analysis, most notably the spatial and temporal scales. The spatial scale includes the extent of the study and the resolution or detail. The spatial extent might be global, national, regional, local, or an individual link in a network. Detail and spatial extent are correlated, but as computer storage continues to increase, this correlation is weakening, and soon there may be national (or larger) studies with very fine spatial and temporal detail. The temporal extent and resolution are also important. A central question is the time horizon of the study, which can range from a single time period (cross sectional) to any duration (longitudinal). Time is also important because of the many cycles that affect the potential for hazards (Cova and Conger 2004).

In the existing approaches for assessing flood hazard in road networks, hazard is assessed with different levels of complexity; some of the approaches are limited to susceptibility.

Hazard analysis starts with a hazard identification and impact analysis. A process source is considered an area that has a uniform predisposition for hazard formation. For water hazards, this area is the water channel and its catchment area. The possible event magnitudes are categorized with recurrence intervals for specific years. The following subsections discuss some approaches and examples to illustrate the procedure.

Modeling for Flood Hazard Assessment

To obtain the intensity associated with a return period, flood modeling is used. Map 3 depicts an example of modeling flooding across a transportation network.

Map 3 shows the depth of the flood in meters, with the direction and velocity of the flood depicted with a vector field. This example is output from the MIKE 21 flood simulation system for modeling two-dimensional free surface flows. The system can model many conditions that occur in a floodplain, including flooding and drainage of the floodplain, embankment overtopping, flow through hydraulic structures, tidal forces, and storm surge (Cova and Conger 2004).

Other, simpler approaches include the use of a Geographic Information System (GIS), such as the method presented by Dawod et al. (2014). This method is based on the idea that the higher the runoff depth is in a sub-basin, the more hazard there will be on roads in that sub-basin. The flood computations are performed on a sub-basin level. Thus, the runoff depth of each sub-basin may be considered the most effectual factor that affects the flood impact. Hence, the spatial analysis tools of the Arc GIS software are utilized to reclassify runoff depths in 10 categories, and each category is assigned a unique number. That number, called the hazard, or danger factor, is assigned to the road in a particular sub-basin. By

Box 1. Blue Spots in Australia

Susilawati and Taylor (2008) studied road network vulnerability in the Green Triangle Region in Australia by using two accessibility indices. The first is the Hansen indices, which measure the integral accessibility of certain places, and the second is the Accessibility/Remoteness Index of Australia, which is developed by the Department of Health and Aged Care (DHAC) in terms of measuring remoteness to access the service center.

The methodology aims at finding out the vulnerability of a road network at the regional level by measuring the changes of the Hansen accessibility indices and ARIA index after one or more links have been degraded. The basic methodology is shown in Figure 4.

Figure 4 Methodology for vulnerability assessment of a road network (Susilawati and Taylor 2008)

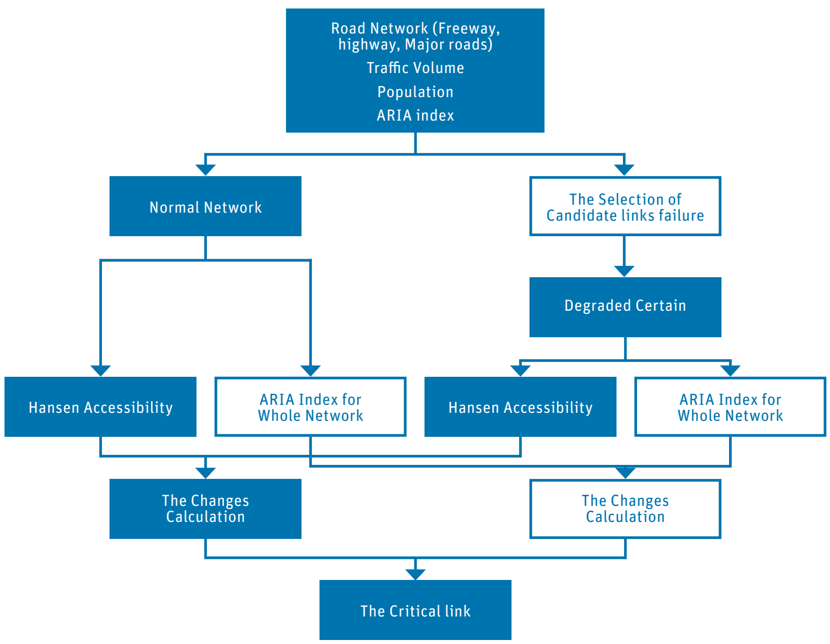
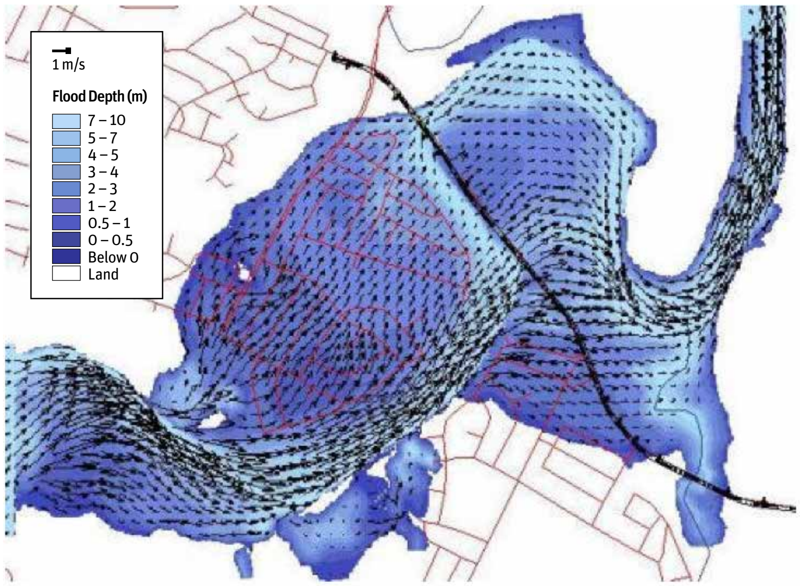


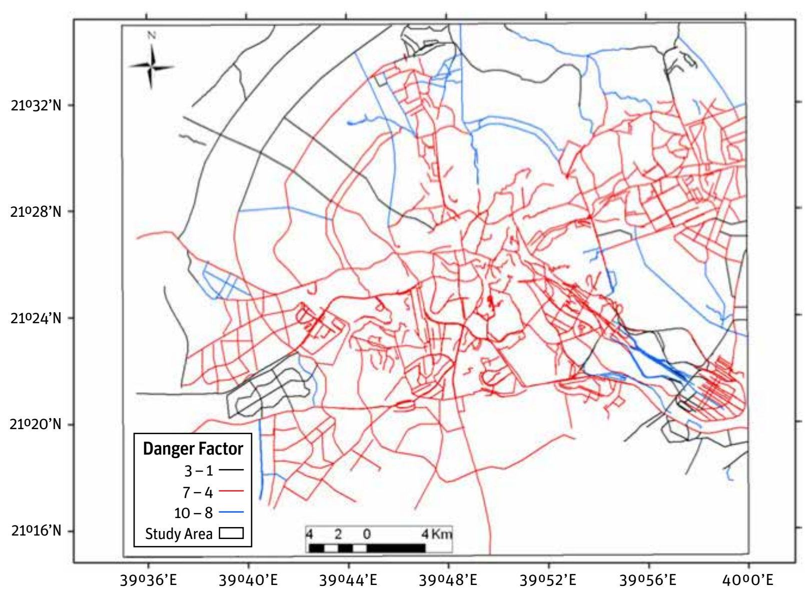
Figure 5 Critical links identified in the study

this approach, each road in the transportation network gets a unique hazard factor (in each scenario), which represents the flood hazard level. The danger factors obtained by Dawod et al. (2014) are on a scale from 1 to 10, with 10 being the highest hazard. The resulting map for Makkah, Saudi Arabia, is shown in map 4.

Map 3 Floodplain Inundation Map over a Transportation Network



Map 4 Danger Factors for the Road Network in Makkah, Saudi Arabia



Source: Dawod et al. (2014).

FEDRO Methodology

In the methodology of the Federal Roads Office of Switzerland (FEDRO), the road has to be taken into account as an element that influences the process (FEDRO 2009). As explained in the section on Interactions between Roads and Floods, the interaction between roads and streams is determinant in hazard conditions.

According to the methodology presented in FEDRO (2009), hazard assessment for roads includes two stages. The first stage, called hazard identification, is comprised of the following steps:

- Obtain, view, and analyze existing information sources.
- Analyze historical events.
- Carry out geological, geomorphic, hydrogeological, and hydrological analysis of the current state.
- Formulate the basic scenarios (known as scenarios of hazard formation).
- Assess the water channel and the existing measures.

The second stage, called impact analysis, is comprised of the following steps:

- Calculate the probability and extent of potential events.
- Create the representation of results and deliverables.

The maps that result from the analysis can show the classification of the hazard. As an example of intensity criteria, table 2 shows the intensity classification according to the FEDRO methodology.

Table 2 Intensity Criteria for the Flooding Process

Hazard process	Weak intensity	Medium intensity	Strong intensity
Flooding	$h < 0.5m$ or $vxh < 0.5m^2/s$	$0.5 < h\ 2m$ or $0.5 < vxh < 2m^2/s$	$h < 2m$ or $vxh < 2m^2/s$
Debris flow deposit	—	$h < 1m$ or $v < 1m/s$	$h < 1m$ or $v < 1m/s$
Embankment erosion			$d < 2m$

Source: FEDRO (2009).
Note: h = water depth or deposit thickness; v = water velocity; d = average thickness of the erosion.

In the FEDRO methodology, the spatial probability of occurrence is determined for each process source, recurrence interval, and field of the intensity map on a case-by-case basis. This process identifies the area or road section length that is affected by a hazardous event in comparison with the entire zone that could potentially be affected by that hazard process for a given scenario.

Susceptibility analysis

Versini, Gaume, and Andrieu (2010a) present a road susceptibility assessment methodology based on the following three steps:

1. Identification of the set of all road sections that could possibly be exposed to flooding. In the proposed methodology, the points exposed to flooding are of three different types: river crossings, low accumulation points, and river adjacent points that can be submerged during river overbank flow events. The identification of all points of the road network belonging to one of these categories is based on analysis of GIS information.
2. Identification of the specificities of the road sections.
3. Definition of the susceptibility rate.

A key aspect in the methodology is the link between the susceptibility of a road to flooding and the dimensions of the river-crossing structures (bridges or culverts) and, more specifically, the adequacy of the opening (cross-section) of the structure and the discharges that may be produced by the upstream watershed during floods (Versini, Gaume, and Andrieu 2010a). Versini, Gaume, and Andrieu (2010a) propose to compare two discharge values for their case study in France: the theoretical maximum free surface discharge capacity through the crossing structure (Q_C), which can be estimated with the Manning-Strickler formula, and the theoretical 10-year return period discharge (Q_{10}) for the upstream watershed, based on a well-established formula adapted to small catchments in France. With these two variables, the ratio Q_{10}/Q_C is estimated and used in the susceptibility analysis. However, Versini, Gaume, and Andrieu (2010) found that the road altitude, local slope, and catchment area were the most important factors for identifying susceptible road sections.

Blue Spots Approach

A widely used approach is blue spots analysis. Blue spots are flood-sensitive areas in the road network (Michael, Høegh, and Søren 2010). A blue spot is a location of the road network that can be flooded in certain circumstances. A blue spot only refers to the probable cause of flooding and not to the consequences; therefore, the identification of a blue spot does not by definition mean that the risk of flooding in that location is unacceptable (Buren and Buma 2012).

The blue spots concept is a chain of procedures for systematically analyzing, adapting, and protecting the road network from flooding. The concept involves computer methods executed on office personal computers, followed by targeted field inspections and actions. The starting point is a screening method that can be used at the regional scale to find blue spots. Depending on the severity of possible conflicts between a blue spot and the road, the level of investigation can be expanded to analyze the rain sensitivity of individual blue spots, or even an additional step of detailed numerical modeling of hydraulic processes. The last procedures of the blue spots concept are inspections at selected local sites, followed by the appropriate actions. These actions may include, for example, upgrading drainage systems or improving the monitoring of water levels in streams. The blue spots concept is intended for use on large and important roads in a nonurban setting (Hansson, Hellman, and Larsen 2010).

The blue spots method is divided into three levels, as follows (Hansson, Hellman, and Larsen 2010):

- **Level 1.** The first level can be described as a screening, where all depressions in the map material are identified. This is done by allowing rain to fall on the model land surface while not allowing for infiltration into the ground or evaporation to the atmosphere. Hence, every drop of rain will flow along the land surface until it reaches a volume of free water collected in a depression. If these volumes are larger than 10 cubic meters and close to a road, they are considered threats and are included in the following analysis.

- **Level 2.** The second level is the calculation of rain sensitivity for each individual depression found in level 1. The calculation is done by assuming no drainage from depressions and assuming impermeability of the catchment of 20, 40, 50, 60, 80, and 100 percent. In this way, a map can be drawn showing the amount of precipitation needed to fill low-lying areas.
- **Level 3.** The third level consists of a 2D-1D hydrodynamic model of surface reservoirs and depressions, which is used to find pathways, catchments, and ponds in an area. The calculation of water flow on the surface and in the drainage systems is taken into account, giving a more accurate calculation of flood hazard.

In addition, the flood hazard caused by sea level rise is mapped by incrementing the sea level and tracking how far inland the seawater reaches. Dikes act as barriers as long as the water level does not exceed the upper limit of the dike.

The flood hazard from water level rise in rivers can be calculated in the same way as for sea level rise. The water level in a river can be incremented to a given level and the effects of the water level rise can be tracked inland (Hansson, Hellman, and Larsen 2010).

Normally, there will be many blue spots along or near a road stretch and level 2 analysis is probably justified in most, if not all, cases. The level 2 analysis focuses on pointing out the most dangerous depressions.

Two depressions of similar geometry (volume and shape) do not necessarily pose the same problem. It is crucial to determine the catchment for every depression to estimate the volume of water available to fill the depression. A large catchment for a small depression means a greater threat than a small catchment for a large depression. Rainfall depth, in millimeters needed to fill the depression, can be calculated by dividing the depression volume by the area of the catchment.

In conclusion, depressions near the road that can be filled by relatively moderate rainfall should be targeted first for inspection and preemptive measures (Hansson, Hellman, and Larsen 2010).

The benefits of implementing level 3 analyses are that the water flows on the surface and in the drainage systems are taken into account, thus providing a more accurate calculation. Level 3 is an excellent tool to use when looking for a solution, including more details about the systems (for example, drainage and storage capacity) and when setting up emergency plans (Hansson, Hellman, and Larsen 2010).

Boxes 2 and 3 show examples of the blue spots methodology applied in the Netherlands and Denmark, respectively.

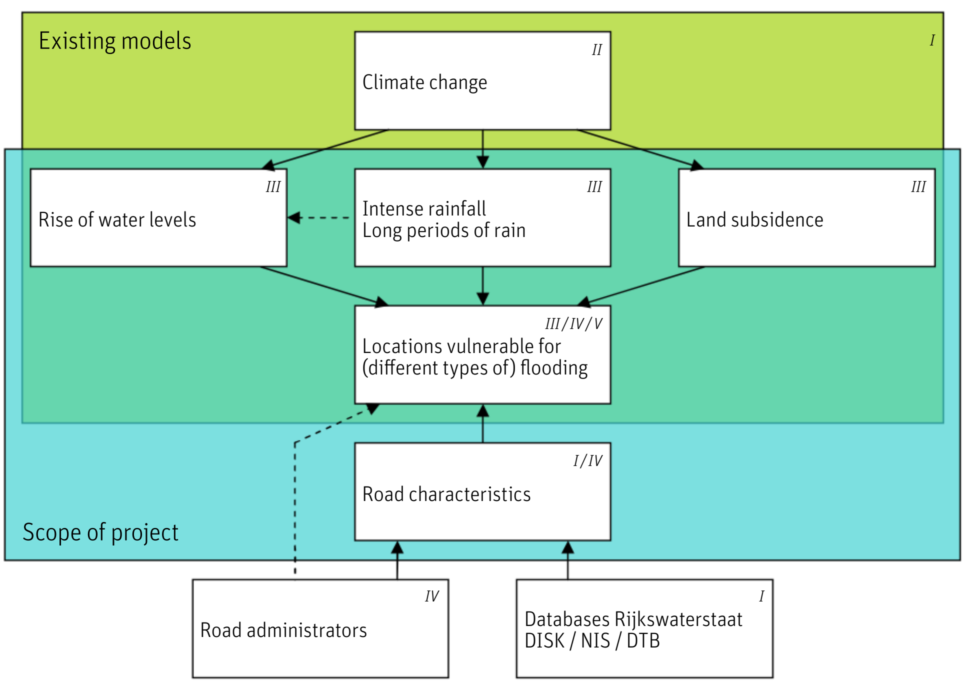
Box 2. Blue Spots in The Netherlands

The methodology applied in the Netherlands for the identification of blue spots is shown in figure B2.1. A significant amount of data is collected to identify the blue spots. These data deal with the road, climate change, and the existing modeling results. To anticipate future climate change, the analysis determines what climate change needs to be dealt with in the project. Climate change is taken into account for the relevant worst-case scenario for various types of climate change in 2050. For the analyses, existing knowledge and modeling results are used as much as possible. In the first phase of the analysis, this knowledge is combined with road information and climate change scenarios to gain a first insight about potential blue spots. Based on location and the height of the road, locations where water heights are higher than road heights are identified. Subsequently, information about the construction of the roads is used to identify other vulnerable spots, as well as locations where water heights do not exceed road heights.

The results of the first phase are based on existing approximate model calculations, and sometimes assumptions and general information about the road. The calibration was performed by comparing the results of phase 1 with the experience of road administrators by interviewing the road administrators in different districts. The calibration also included verification of potential blue spots that were identified in the first phase, as the identification of still unidentified blue spots.

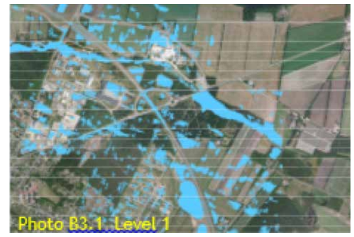
The identified potential blue spots are not necessarily the actual vulnerable spots in the road sections. For instance, there may be facilities that prevent flooding, or the design of the road may be very robust. The last phase of the analysis zooms in on the identified potential blue spots from the previous steps to filter spots that are not vulnerable from the potential blue spots. A list of more likely vulnerable blue spots is the result of this last analysis. These more likely blue spots can later be analyzed to verify whether they are actual blue spots.

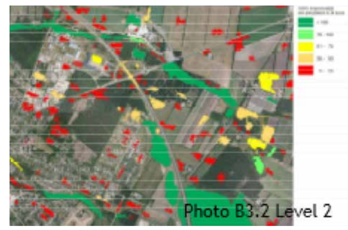
Figure B2.1 **Methodology Applied in the Netherlands for the Identification of Blue Spots**

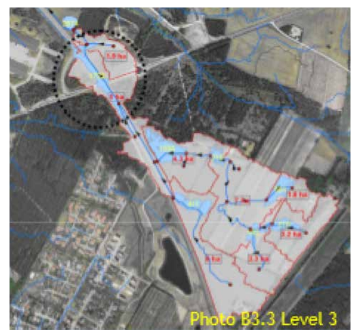


Box 3. Blue Spots in Denmark

The three levels of the analysis are as follows:







Level 1: screening using terrain analysis. All the depressions are identified, assuming a surface runoff of 100 percent in the catchment (that is, no infiltration of rainwater into the soil) (photo B3.1). Low-lying areas where there is danger of flooding due to rising sea level are identified. Various levels of sea level are used. Dikes are included so that no flooding behind the dikes occurs unless water levels exceed the height of the dikes. This level does not take into account the gradients in streams.

Level 2: rain sensitivity for individual depressions. Flow paths and catchment areas for each blue spot are calculated. This is a simple calculation from contributing areas. A map is created with the amount of precipitation needed to fill low-lying areas. This level assumes there is no drainage from depressions. Rain sensitivity analysis is done with impermeability of the catchment area of 20, 40, 50 , 60, 80, and 100 percent (photo B3.2).

Level 3: hydrodynamic model of surface reservoirs and depressions. This level provides a time-variable flooding prediction. It has 2D-1D coupling between the surface (terrain, canals, and ponds) and drainage systems (pipes) (photo B3.3).

After pointing out all the blue spots on the road network on a level 2 basis, it is often necessary to minimize the numbers for further evaluation. Minimization can be done by risk analysis. Figure B3.1 shows the matrix of a simple risk analysis where the left column gives the probability of an event.

The changing climate will change the probability of some weather extremes, for example, from rare to possible, meaning that the climate scenarios will happen more often. Today the climate has already changed so much that some rainfall incidents with a return period of 100 years have changed to a return period of 20 to 50 years. The consequences for road users and roads are illustrated in the top row in Figure B3.1. The same rainfall event can have different consequences for different types of roads. The number of users also has an influence on the consequences, for example, stopping 500 road users because of a blue spot does not have the same consequence as stopping 5,000 road users.

Figure B3.1 Simple Risk Analysis Matrix

	Insignificant	Minor	Medium	Major	Catastrophic
Certain					
Likely					
Possible					
Rare					
Unlikely					

a) All depressions are identified assuming 100% catchment runoff and no drainage in the depression.
b) Rain sensitivity analysis with impermeability in the catchment area of 20%.
c) Pathways, catchments and ponds in a risk area are calculated by the use of 1D-1D and 1D-2D modeling.
Note: The probability is in left column and the consequences are on the top.

RISK ANALYSIS

In the most general form, risk R can be defined as $R = H \times C$, where H is the probability of a threatening event (hazard) and C are the consequences related to H. The consequences C are a product of the value of the elements at risk E, and their vulnerability V, such that the risk equation becomes $R = H \times E \times V$. Vulnerability V is a factor between 0 and 1, indicating the severity of expected loss given a hazard H, and expressed as a fraction of the total value of E. In the context of network vulnerability, monetary values of road segments (pavement, side rails, etc.) can be included to refer to the structural vulnerability of the elements at risk. Hazard H may express the probability of occurrence of a potentially damaging phenomenon within a given time period and area (Meyer et al. 2014).

Most risk calculation methods use so-called static traffic values to assess the risk. The number of vehicles on a road section is defined by an average number of vehicles per time unit (daily or annually, for example, annual daily traffic) and by assuming that all vehicles travel at the same speed. Generally, two types of risk are calculated: (i) object risk, which is the probability that a driver is killed among the total number of persons passing through the hazardous area, and (ii) individual risk, which is the probability that a driver passing N times per day in a hazardous area is killed (Voumard et al. 2013).

Risk equations for road networks are shown in table 3.

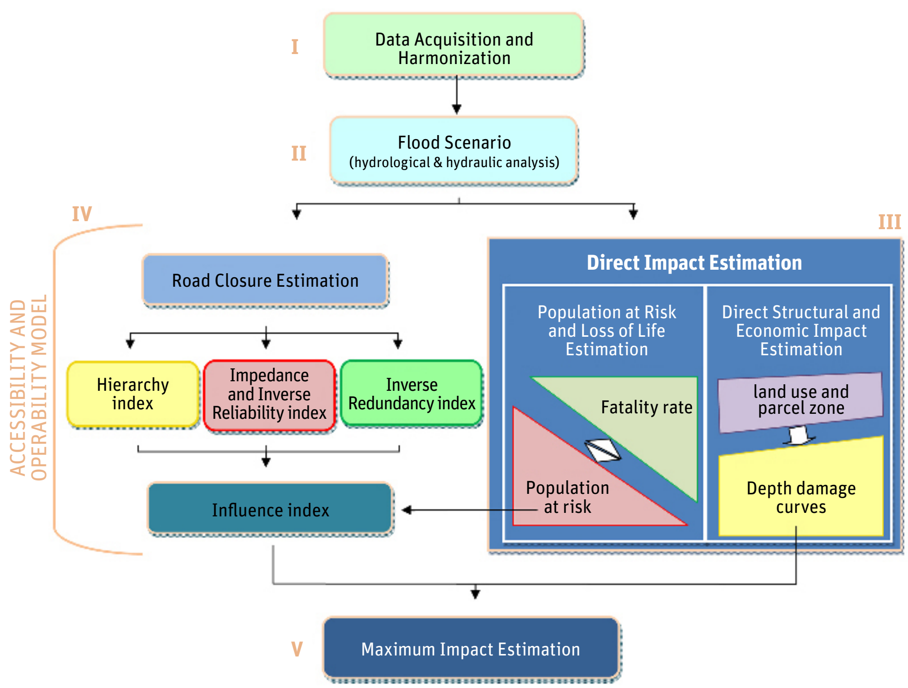
Table 3 Risk Equations

$R = \sum_{i=1}^{N} H \cdot Exp_i \cdot V \cdot W$	R is the risk [dead yr] or [USDyr] with n objects, H is the hazard [yr], Exp_i is the object exposure, that is, the probability that a vehicle is hit in the hazardous area, V is the object vulnerability, and W is the potential total loss of persons or costs ([dead] or USD]).
$R_{ob} = F_e \cdot P_s \cdot N_v \cdot \lambda \cdot ß$	Object risk on a road where R_{ob} is the object risk [dead yr], F_e is the frequency of occurrence of an event [yr], P_s is the proportion of the hazardous section that is affected when a hazard occurs, λ is the probability of death when a vehicle is damaged by a hazard, ß is the average vehicle occupation [persons/vehicle], and N_v is the number of equivalent vehicles permanently exposed in the hazardous area: $N_v = \frac{N_{v\_tot}}{f} \cdot \frac{l}{v}$ where $N_{v_}$tot is average number of vehicles per day [vehicles day], l is the length of the hazardous section [m], v is the average vehicle speed [km h], and f is a conversion factor to convert the speed from [km h] to mday. F_e and P_s represent H, where P_s allows the hazard on a road section to spread. N_v is the sum of exposures (Expi), λ is the vulnerability V, and ß is the losses W.
$R_{ind} = \frac{R_{ob} \cdot X}{N_{v\_tot} \cdot ß}$	Individual risk, where X is the amount of time that a person passes every day through the hazardous road section [day].
$R_{ob} = F_e \cdot P_s \cdot N_v \cdot \lambda \cdot ß = F_e \cdot P_s \cdot \frac{t_{cum}}{t_{sim}} \cdot \lambda \cdot ß$	Dynamic object risk with notation as in the above equations, where t_{cum} is the accumulated time of vehicles observed in the hazardous area and t_{sim} is the simulation time of a dynamic risk model.

The hazard and vulnerability data that are used in the equations shown in Table 3 can be obtained from the application of the methodologies described in the previous sections. An example of the use of these mathematical approaches for the calculation of flood risk on a road network is presented in Meyer et al. (2014). The method focuses on expenditures on additional traffic loads resulting from road closures, and thus the functional value of the network links. The product of traffic volume [vehicles day], excess distance [km], and closure time [days] gives the total additional average traffic load per road closure [vehicles × km]. Assuming that characteristic closure times amount to 1 day, the multiplication of link-failure likelihood [1 year] by additional traffic load results in the annual flood-related link risk [vehicles × km year].

The use of GIS plays an important role in most existing methodologies. For example, Albano et al. (2014) propose a framework, integrated in a GIS, to estimate the direct and indirect damages from a flood event. The objective is to understand the strengths and fragilities of a particular urban area, including main roads, secondary and local roads, bridges, etc. The methodology proposed by Albano et al. (2014) is shown in figure 6. Accessibility indexes are used (see the section on Vulnerability) in combination with a direct impact estimation to obtain an estimate of the maximum impact.

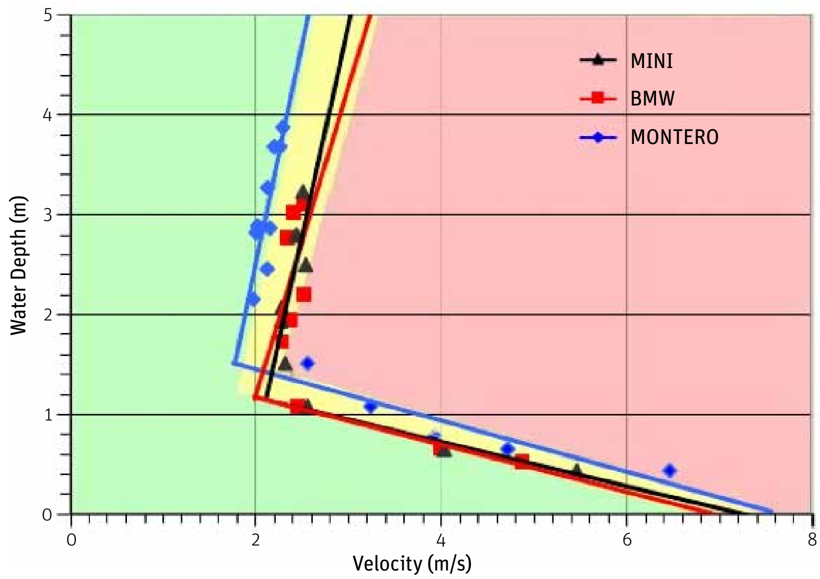
Figure 6 Framework for Estimating Direct and Indirect Damages from a Flood Event



Source: Albano et al. (2014).

The methodology illustrated in figure 6 allows the analysis of emergency response. Road closures caused by floodwaters, estimated on the basis of velocity and water depth values, could cause damages and hence could alter emergency travel operations from normal conditions. Analysis of the paths of the emergency travel activities could provide the possibility to estimate the operability of the strategic emergency structures and highlight weaknesses (for example, the most inaccessible area at risk or a strategic connectivity road that is most damaged). If the vehicles on any street are dragged by the water flow, the road is inaccessible. The methodology uses the envelope curves developed by Teo et al. (2012), as shown in figure 7. The curves are shown in three color zones (green, yellow, and red), and the hydraulic stability for each idealized vehicle is easily identified by color. The stable zone is shown in green (on the left in the figure), the transition zone in yellow (in the center of the figure), and the unstable zone in red (on the right in the figure). All vehicles in the red zone of the graph are dragged by the water flow; hence, for example, the vehicles could block an emergency vehicle during rescue actions.

Figure 7 **Critical Threshold Values of Hydraulic Instability for Specific Vehicles**



Source: Teo et al. (2012).

As shown in figure 6, the following indexes are estimated:

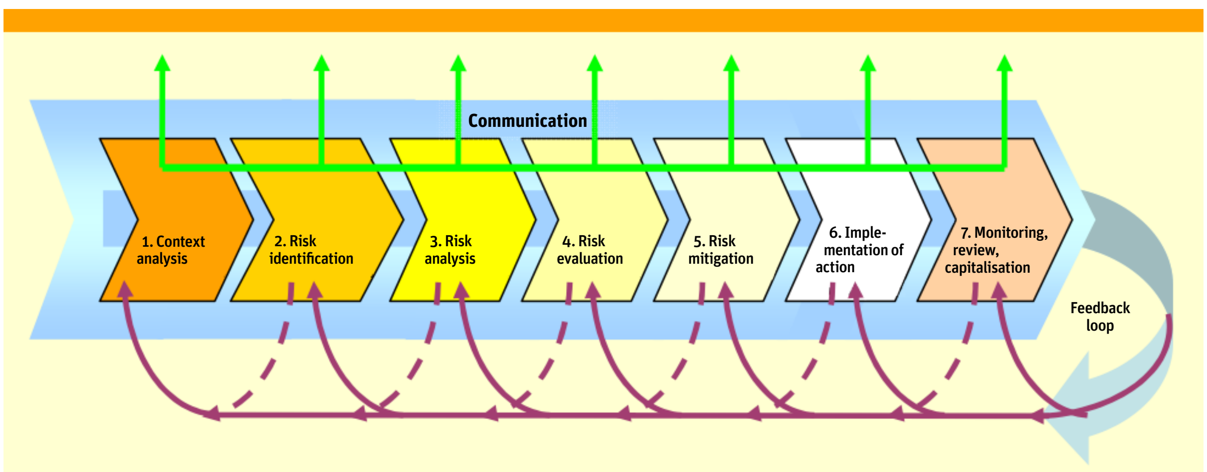
- The inverse reliability index highlights the travel distance reliability of the path. Travel distance reliability considers the probability that a trip between an origin–destination pair can be completed successfully via the shortest distance possible for the normal functioning of system connections.
- The impedance index is the degree of inaccessibility of an area that requires rescue.
- The hierarchy index is an estimate of the strategic importance of single arches. A network link is critical if loss or substantial degradation of the link significantly diminishes the accessibility of the network or particular nodes.
- The inverse redundancy index suggests the number of potential alternative connections between one arch and others related to it considered in the emergency phase. Therefore, the index provides information on the number of available and unavailable arches, in the case of flooding, for emergency services if the arc is inoperable.

The methodology combines these indexes to produce an influence index that takes into account the role of each element in the system in the emergency phase. Finally, estimation of the direct economic consequences is coupled with the indirect systemic impact in emergency management through a maximum-impact index (for details of the analysis, see Albano et al. (2014)).

The use of multi-criteria analysis is proposed by the RIMAROCC methodology (Bles et al. 2010). Figure 8 shows the framework for the methodology. The figure depicts a cyclical process that continuously improves performance and capitalizes on experience. The process starts with an analysis of the general context where risk criteria are established, and ends with a reflective step where the experiences and results are documented and made available to the organization.

The steps and sub-steps of the RIMAROCC methodology are shown in table 4. In the first step, objectives are defined as well as the external and internal parameters to be taken into account, the scope and the risk criteria for the remaining steps. The second step entails the identification of sources of risk, areas of impact of unwanted events (including changes in circumstances), and their causes and potential consequences. The third step, risk analysis, involves developing an understanding of the risks. The risk analysis provides input to risk evaluation and serves as a decision basis for determining whether risks need to be treated, and for selecting the most appropriate risk treatment strategies and methods. The fourth step, risk evaluation, involves comparing the level of risk found during the analysis process with risk criteria established when the context was considered. Based on this comparison, the need for treatment can be considered. Risk mitigation is the fifth step, which involves identifying, appraising, and selecting one or more options for modifying unacceptable risks. In the sixth step, the action plan is developed in detail; responsibilities for implementation are addressed, resources are allocated, and performance measures are selected. Since risk management is a learning process, the seventh step aims to monitor and review the implemented actions and capitalize on the knowledge gained from climatic events and the implementation of action plans. If conditions change, re-planning starts within this step (Bles et al. 2010).

Figure 8 **Framework of the RIMAROCC Methodology**



Source: Bles et al. (2010).

Table 4 Steps and Sub-Steps of the RIMAROCC Methodology

Key steps	Sub-steps
1. Context analysis	1.1 Establish a general context 1.2 Establish a specific context for a particular scale of analysis 1.3 Establish risk criteria and indicators adapted to each particular scale of analysis
2. Risk identification	2.1 Identify risk sources 2.2 Identify vulnerabilities 2.3 Identify possible consequences
3. Risk analysis	3.1 Establish risk chronology and scenarios 3.2 Determine the impact of risk 3.3 Evaluate occurrences 3.4 Provide a risk overview
4. Risk evaluation	4.1 Evaluate quantitative aspects with appropriate analysis (CBA or others) 4.2 Compare climate risk to other kinds of risk 4.3 Determine which risks are acceptable
5. Risk mitigation	5.1 Identify options 5.2 Appraise options 5.3 Negotiation with funding agencies 5.4 Formulate an action plan
6. Implementation of action plans	6.1 Develop an action plan on each level of responsibility 6.2 Implement adaptation action plans
7. Monitor, re-plan and capitalize	7.1 Regular monitoring and review 7.2 Re-plan in the event of new data or a delay in implementation 7.3 Capitalization on return of experience of both climatic events and progress of implementation

Source: Bles et al. (2010).

A crucial step in the RIMAROCC methodology is to identify the criteria, indicators, and risk evaluation categories to be used. These aspects will be transformed into a risk matrix and used in a multi-criteria analysis. The criteria should correspond to the scope and scale of the system under investigation.

Since road networks are used by different players from an economic and social perspective, the RIMAROCC methodology specifies recommended data collection that should be adapted to the scale and objectives of each specific study and that includes social, economic, and political data to establish the context of the analysis. The collection of data and subsequent analysis require the participation of several stakeholders, normally entailing intense inter-institutional work. The data collection includes, but is not limited to, the following (Bles et al. 2010):

- **External context data.** These are data on the social and cultural, political, legal, regulatory, financial, technological, and economic context, as well as the natural and competitive environment context, at the international and national levels; key drivers and trends that have an impact on the objectives of the road authorities; and relationships with and perceptions and values of external stakeholders.
- **Internal context data.** These are data on governance, organizational structure, roles, and accountabilities; policies and objectives and the strategies that are in place to achieve them; capabilities, understood as resources and knowledge (for example, capital, time, people, processes, systems, and technologies); relationships with and perceptions and values of internal stakeholders and the organization's culture; information systems, information flows, and decision-making processes (formal and informal);

standards, guidelines, and models adopted by the road authority; and the form and extent of contractual relationships.

The internal and external contexts are highly important in assessing the consequences of events involving risk factors for the multi-criteria analysis. The consequences are classified as direct (disruption of the road system, activities, and/or infrastructure) and indirect (human and socioeconomic impacts). Indirect impacts relate to the consequences of the climatic event on the well-being of the users (including psychological impact, stress, and tiredness), safety (casualties), the local or regional economy (economic losses), etc. In some cases, specific studies are required to establish the social and economic costs to society.

According to the RIMAROCC methodology, the impact of risk can be determined in the following categories (Bles et al. 2010):

- Integrity of people (users and employees), that is, persons killed or injured
- Damage to infrastructure, that is, cost of restoration
- Operating losses for road managers (revenue, quality of service, image) and users (loss of time, additional cost of using vehicles)
- Damage to the environment (image and degradation)
- Economic and social consequences for the nation, region, or area of influence (impact on modal choices, impact on accessibility of local territories, and role of transportation in the global economic system)
- Cost of palliative solutions should also be determined.

RISK REDUCTION

Reducing risk for a specific segment of a road network means influencing the occurrence, frequency, or intensity of disasters, and reducing the vulnerability of a given segment. In the case of a decrease in the probability of the occurrence of a natural disaster, monitoring is used for timely warning, flood control modifications are made in beds of water flows, and appropriate planting of forest cover is carried out, among other measures (Bil et al. 2014).

Reducing the vulnerability of a road segment can include the following:

1. **Enhancement of road segment resistance.** Road segments endangered by a natural disaster must be adjusted to enhance their physical resistance. For this purpose, construction adjustments can be carried out. Examples include converting communications on embankments, creating deeper road foundations on slopes, and enhancing drainage structures. Vulnerability reduction is sometimes carried out together with the reduction of another threat. For example anti-flooding measures can also reinforce the original road (Bil et al. 2014).

2. **Optimization of a road network.** It is preferable to ensure that detour routes can be used, in the case of a failure. Bil et al. (2014) provide an example of optimization algorithms.

3. **Maintenance.** The road management staff has the responsibility to organize inspections and maintenance in an appropriate way. Staff needs to work with information retrieval, to evaluate whether the redesign of existing drainage systems is necessary, and finally to determine a specific action plan for inspections and maintenance. Information-related activities should focus on the following (Hansson, Hellman, and Larsen 2010):

    - Hazard and vulnerability information
    - Background information at the site
    - The current drainage system
    - Feasibility of monitoring (early warning) systems
    - Preservation of information in a database.

4. **Monitoring.** Local weather stations and, for example, water level measurements in a retention pond or culvert may provide valuable information on how the system responds to specific weather conditions, like heavy rain. Changes in the response over time also provide good clues to when maintenance is needed. Monitoring systems may include the following (Hansson, Hellman, and Larsen 2010):

    - Local weather stations.
    - Water-level sensors in manholes, wells, groundwater tubes, culverts, retention ponds, streams, and reservoirs. Water-level readings can be directly converted to water flow if a discharge curve is determined for the measurement site.
    - Video cameras.

It is strongly recommended to create a database in which, for example, the following information can be stored (Hansson, Hellman, and Larsen 2010):

- Inspection notes, check lists, photos of the situation, and other comments about the site
- Information about maintenance and repair work
- Damage to the road and drainage
- Flooding events
- Improper dimensions.

5. **Flood early warning.** The purpose of flood early warning systems is to give the responsible persons some time to consider appropriate measures before the real problems start. Anticipating the state of a road network during a flood can be helpful to prevent traffic from using roads at risk and identify the safest access routes to the affected areas for rescue services (Versini, Gaume, and Andrieu 2010a). The cause of the problem in this case is typically a storm with heavy rainfall, rapid and massive spring snowmelt, or high river flow. Close cooperation with meteorological and hydrological institutes is required to receive warnings about upcoming problems.

   An early-warning system may comprise the following:

   - A weather alert notification system
   - Information and data retrieval from monitored sites
   - Risk assessment based on weather alerts and conditions at the site
   - In case of severe risk, presentation of information to road users about alternative routes, for example, by signs, radio, or suitable information technology
   - Inspection and preparation of the site for harsh conditions
   - Arrangement of warning signs and lights with adequate information.

   Versini, Gaume, and Andrieu (2010b) present an example of a flood early warning system for a road network for which warning levels were defined from the distribution of flooding return periods and simulated discharges from a distributed hydrometeorological model.

CONCLUDING REMARKS

Road networks are critical infrastructure. Therefore, appropriate incorporation of risk information in the planning and operation processes for road networks is crucial. Road networks and flood hazards interact in such a way that roads cannot only be damaged by floods, but also roads can enhance hazardous conditions. Thus, it is highly important to consider the interaction between roads and floods during the planning and design process, generating integration between road planning and design and flood risk management.

The vulnerability of road networks is an active field of research, and several approaches currently exist to assess vulnerability. This report presented multi-criteria analysis techniques, serviceability analysis, and accessibility indexes. The choice of method of analysis depends on the purpose, scale, and available data; however, the main purpose of all the methods is to identify where and how disruptions of road networks may be particularly severe.

The approach to be used in flood hazard analysis depends on the scale, type of flood, purpose of the analysis, and available data. This report presented a non-exhaustive number of examples to illustrate some of the methods currently used for flood hazard analysis, with a focus on road networks. Complexity can vary from highly detailed hydrologic and hydrodynamic modeling to simpler susceptibility analysis techniques to identify potentially problematic areas. Hydrologic and hydrodynamic modeling offers the advantage of providing detailed information for planning and design purposes, with the disadvantage of being data demanding. Susceptibility analysis provides the possibility to address larger areas with a limited amount of data.

Several approaches for risk assessment were presented in this report. These include risk equations, the use of GIS incorporating indexes, and the use of multi-criteria analysis proposed in the RIMAROCC methodology. Due to the high complexity of road networks and the associated risks, risk analysis can be as complex as needed, incorporating aspects such as damage to infrastructure, operating losses, damage to the environment, and economic and social impacts.

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