Chapter

Risk Matrixes as Environmental Management Tools

Alice Elizabeth González, Martín Paz Urban, Martín Goyeneche and Lady Carolina Ramírez

Abstract

Within the framework of a broader project, the vulnerability to climate change of roadworks of art (bridges and culverts) was analyzed. A hydrological study was done; a set of preselected bridges and culverts was characterized. A methodology was proposed to work with risk matrices in order to determine an investment prioritization criterion from this point of view. This methodology was applied to the preselected set of bridges and culverts intended to have higher vulnerability to climate change (because of their years in service, their design, current scour depth, and so on). The proposed methodology was implemented in detail in two specific cases and turned out to be robust and easy to apply.

Keywords: risk matrices, climate change, vulnerability, environmental management, bridges and culverts

1. Introduction

1.1 Risk and risk assessment

Risk can be defined as the probable damage that a disaster can cause according to certain conditions of threat and vulnerability (Ferradas in [1]). Risk implies the existence of future or hypothetical damages, the occurrence of which depends on certain conditions that can be assumed to be human or environmental causes (Hurtado et al. in [1]). Some disasters are caused by environmental phenomena that cannot be neutralized, although in some cases they can be partially prevented.

Thus, risk is defined as a combination of the probability of an event occurring and its consequences, including its severity [2]. The identification and assessment of risks is carried out through the analysis of threats (natural or anthropic phenomena that may arise) and the vulnerability of potential recipients. Risks are identified and assessed through methodologies that consider the probability of occurrence of a risk event and its consequences, in order to determine the level of current risk [1].

The IPCC's approach to vulnerability and risk is now broader than the "classical" approach that used to be focused on extreme events, probability, and uncertainty. Through a comprehensive vision, Cardona et al. [3] propose that:

IntechOpen

> *"Understanding disaster risk management as a social process allows us to change the focus of disaster response toward an understanding of disaster risk (…). This requires to know how human interactions with the natural environment lead to the creation of new hazards and how people, property, infrastructure, assets, and the environment are exposed to potentially harmful events. Furthermore, it requires an understanding of the vulnerability of people and their livelihoods, including the allocation and distribution of social and economic resources that can work for or against the achievement of resistance, resilience, and security."*

When referring to extreme events, vulnerability may be less critical than for the case of events with a higher probability of occurrence and lower intensity. However, for the latter, vulnerability has a strong relationship with small and recurring disasters. To promote more resilient societies with greater adaptive capacity, it is necessary to understand what risk is about and learn to manage it. Anticipating the occurrence of an adverse event, being able to prevent it or capitalizing on the consequences of an event to reduce the impact of future events, may contribute to reducing risk and, consequently, to better allocate resources. Reducing the exposure and vulnerability of a certain community to a type of event might increase the risk for another community in the area; this is why it is necessary to assume the need of a plan with a systemic approach [3]. Risk management aims to reduce the probability of occurrence of the adverse impacts of an event. Risk can be represented in several ways, but here it will be seen as a function of the danger or threat and the vulnerability or susceptibility of the recipient to being overwhelmed by that danger. Therefore, correctly determining the factors involved will help create a clear and representative risk matrix.

The existence of a risk will imply the presence of a disruptive agent or hazard, which is likely to cause harm. These adverse effects will be of different nature and intensity depending on the level of vulnerability of the infrastructure that is affected [4].

According to [5], risk analysis should always be a participatory process developed with the community, with or without information generation or explicit engineering participation. When using engineering analysis, two components must be quantified: the probability of the risk and the severity of its consequences. The probability of the risk is the probability of failure of the system or one of its elements. The consequences and their severity can be obtained by applying typical engineering tools, which classify the risk according to the expected consequences and whether or not they are acceptable for the cultural thresholds of the place [6].

Vulnerability and risk assessments are key strategic activities that inform both disaster risk management and climate change adaptation. They require the use of reliable methodologies that allow adequate estimation and quantification of the potential losses and consequences of a risk event for human systems, in a given exposure time. At the local level, there is usually a lack of information to carry out a detailed analysis. However, it is desirable that these evaluations can be carried out locally to achieve the best possible result for a given community [7]. Therefore, it is common to have to resort to criteria to simplify or aggregate the available information since either basic quantitative information is missing or the information available does not have the level of detail that would be useful.

The most common way to represent the probabilistic nature of hydrometeorological phenomena is in terms of a return period Tr, which is the period of time that, on average, elapses between the occurrence of phenomena of a certain intensity [8]. The aim is to model using different return periods and obtain a range of responses to different scenarios. Therefore, the dangers have to be identified, enumerated, and determined, maintaining short- and long-term perspectives, taking into account the duration and intensity of the events, and performing an analysis of the suitability of the territory, that is, prepare a diagnosis of the location area and the current condition of each bridge. The level of detail achieved by this analysis will depend mostly on the availability of the data. On the other hand, the considered characteristics of the hydrometeorological events of interest must be carefully chosen, in order to obtain a representative set of factors to evaluate.

In European countries, there are systematic studies on the risks involved in major floods, focusing on their multisectoral consequences [9, 10]. Risk indicators include the occurrence of heavy rainfall, such as a history of flooding that can generate adverse impacts on the socioeconomic system and ecosystem services. These include flash floods, the frequency of which is expected to increase, especially in summer. Directive 2007/60/EC, the current version of Directive 2000/60/EC on operational aspects of the water policy of the European Union, is currently in force [9]. Among other provisions, the current directive suggests the construction of flood risk maps and the development of flood risk management plans, with a focus on prevention, protection, and training of people. The abovementioned directive requests flood extent maps for a scenario of low probability of occurrence (the return period is not established, but some countries have used 300 years and others, such as Sweden, have used the flood of Tr = 10,000 years) and another with medium probability (Tr ≥ 100 years). The expected flood limits should be presented on a chart, together with roads, buildings, water bodies, and so on. For flood management, it may be also useful to map the water depth, the flow velocity, or its danger (as a combination of the return period and the severity of the event), among other information [10].

Article 4 of the directive indicates the following minimum contents for the preliminary flood risk assessment; regarding the content of flood danger maps and flood risk maps, their content is also established in the directive. For threat maps, three scenarios with different probabilities of occurrence must be considered [9]:

a. *"low probability of flooding or extreme event scenario;*

b. *average probability of flooding (return period ≥ 100 years);*

c. *high probability of flooding, when applicable."*

For each of them, the extent of the flooding, the water depth, and, where appropriate, the corresponding flow velocity must be indicated. For flood risk maps, the approximate number of inhabitants that may be affected, the economic activities within potentially affected areas, and the identification of facilities that may cause pollution problems during a flood must also be presented [9].

The flood emergency management system (FEMS) is also operational in the European Union [11]. The European Commission, through its EU STAR – FLOOD1 project, proposes a new way to assess and monitor the effectiveness of FEMS, applying seven indicators that must be evaluated at the national level: planning (if there is an operational plan in case of emergency due to flooding); institutional learning (e.g., post-event reviews and consultations, opportunities for knowledge exchange between responding agencies); emergency situation drills; joint work; community training; provision of resources; and recovery-based activities. A scale of one to five is used for each criterion. As both the frequency and severity of floods are expected to increase due to climate change, societies must prepare to cope. Therefore, the evaluation was implemented in five countries (France, Netherlands, Poland, Sweden, and the United Kingdom, more specifically, England) [11]. As a result, important differences were evident between different countries in terms of the risk of suffering floods. For example, the consequences on infrastructure, for example, bridges, are included in the section related to risks for economic activity. The countries that have reported a greater number of vulnerable points for events with a medium probability of occurrence are Italy, Spain, Portugal, and the United Kingdom. From this primary evaluation, several opportunities and constraints are identified to improve the effectiveness of FEMS in Europe. Therefore, the assessment framework is an important factor in impulse further research in this area [12].

An interesting precedent is presented in Ref. [13]. The work presents the development of a method that uses GIS tools to evaluate the danger, vulnerability, and exposure to flood risk in an area of Salamanca. A nonstructural measure is proposed for the prevention and mitigation of the risk of extraordinary floods. The methodology used to analyze the flood risk was based on the exploration of the physical environment, and it was used in a combined and complementary way for the hydrological-hydraulic model using GIS (ArcGis 10.1). Hazards, vulnerability, and exposure were mapped, with the final objective of evaluating risk through the multiplication of the values of these three elements [13].

1.2 The Fine's matrix

Currently, many of the quantitative tools for risk analysis derive from William Fine's matrix (1971, as mentioned in Ref. [14]), which has derived in what is currently known as the "risk matrix". Risk matrices are usually applied both in occupational safety and environmental issues, business risks, and other applications, due to the ease with which it allows interventions to be hierarchized/prioritized.

Fine proposes to jointly analyze factors of the system under study (internal factors) and threats coming from the external environment (external factors), in order to identify, assess, and prioritize the potential risks that external threats can adversely affect the internal factors of the system and, consequently, cause damage. Quantitatively, prioritization arises from putting values on these factors and assigning a risk value that is a product of the probability of occurrence of the threat, the (frequency of) exposure to the threat, and the severity of the consequences [14].

Most current methods simply multiply the probability of occurrence by the severity of the consequences or impacts. One of them, widely disseminated, is the method advocated by the INSHT of Spain in its NTP 330 [15]. This is a simplified method, based on levels or intervals of occurrence and not on values themselves. The risk level (RL) is considered to be the multiplication of a probability level (PL) by a consequence level (CL). In turn, the PL value arises from the product of the deficiency level (DL) and the exposure level (EL). The value of DL connects risk factors in terms of their possible direct relationship with the occurrence of an accident. This is a concept analogous to that of vulnerability; the higher the DL, the greater the probability that the accident will occur, as long as there is a least frequent EL (not occasional or sporadic) at the same time. Thus, the PL can be very high, high, medium or low. Regarding the level of consequences, they can be classified as mild, serious, very serious, or catastrophic (in the case of accidents, they are said to be fatal). By crossing both values, the risk level and the intervention level are obtained, which can be ordered into four categories: intervention level I (critical situation that needs urgent

	Risk levels – Consequences levels.		
Probability	**Slightly Harmful**	**Harmful**	**Extremely Harmful**
Low L	Trivial risk	Tolerable risk	Moderate risk
Medium M	Tolerable risk	Moderate risk	Major risk
High H	Moderate risk	Major risk	Intolerable risk

Table 1.
Risk factor matrix for occupational accidents (adapted from [16]).

correction); intervention level II (correct and adopt control measures); intervention level III (improve if possible; it would be convenient to justify the intervention and its profitability); intervention level IV (do not intervene, unless a more precise analysis justifies it) [15].

Universidad del Litoral [16] takes up this method and makes two valuable adjustments, which are to convert the consequences to monetary costs and to define in a simpler way the scores for the evaluation of exposure and probability (thinking about accidents at work). It also simplifies the intervention categories, according to the degree of danger of each risk: high (immediate intervention to end or treat the risk); medium (short-term intervention); or low (long-term intervention or tolerable risk) [16].

Once the different risk magnitudes have been obtained, it is necessary to obtain the severity of consequences; in occupational safety, it is quantified according to the repercussions level, which refers to the number of people exposed to the considered danger. Finally, it is possible to have an order of action priorities, always starting with those that are in the high danger-high repercussion zone. Significant risks will consider those whose degree of prioritization is high and medium with a high, medium, or low repercussion, respectively. The severity level may be reduced if corrective measures are applied that reduce any of the factors, consequences, exposure, and probability, so the importance of prioritization would change. In [16], the matrix in **Table 1** is attributed to INSHT.

Two other possible scales of interest arise from [17]: a probability of occurrence scale and a scale to justify the investment.

Probability scale: almost certainly (it is the most possible result); very possible (almost possible, 50% probability); possible (it is a rare but possible coincidence); hardly possible (it is a very rare coincidence, but it has already happened); remote (extremely rare but conceivable); almost impossible (it has never happened in several years of exposure).

The scale to justify the investment to be made is proportional to the percentage of reduction of risk. It has three levels: in-doubt investment, normally justified investment, and fully justified investment [17].

2. Case study

The case study relates to an inter-institutional experience within the framework of the Road Rehabilitation and Maintenance Program 8733-UY financed by the World Bank. It was carried out between the Department of Environmental Engineering of the Institute of Fluid Mechanics and Environmental Engineering (DIA-IMFIA) of the Faculty of Engineering of the Universidad de la República (FING-UdelaR) and the Ministry of Transportation and Public Works (MTOP) of Uruguay, through its National Administrations in Planning and Logistics, Highways, and Topography [4, 7]. The objective was to satisfy certain contractual commitments related to the resilience of road infrastructure in the face of climate change, which involved the development of three technical reports associated with the evaluation of existing infrastructure in the face of hydrometeorological events. A working group was formed ad hoc, called "Road Resilience to Climate Change Group" (hereinafter, GRVCC). The work team was very successful in technical analysis, discussion, and exchange, which allowed for building and putting into practice an effective and robust methodology; solid results were obtained to achieve the pursued objectives [4, 7, 18].

The methodology to be applied was framed in the current approach of the IPCC on vulnerability and risk [3], which focuses on events of lower intensity but with a higher probability of occurrence. The Ministry's Engineers selected a set of 20 bridges expected to have greater vulnerability to intense hydrometeorological events, due to their location, age, characteristics, and history of the last 25 years [7]. This type of event has been hitting Uruguay with increasing frequency and intensity in recent years [19]. For this set of bridges, a detailed analysis of its characteristics was carried out by modeling for events with three return periods with the free-use software HEC-RAS [20] was performed, supported by the open-source GIS software QGIS. In this case, the simulations were made by using three different precedent soil moisture conditions (dry, medium, and humid) [21] and for three return periods (Tr = 50 years, Tr = 100 years, and Tr = 1000 years) [7, 18].

The direct and indirect socioeconomic costs derived from its occurrence were evaluated, with the objective of not only anticipating attention to adverse impacts but also allocating sufficient resources to monitoring and preparation tasks and strengthening the resilience of the communities. The allocation of devoted resources to these latter aspects is part of the necessary cultural change that current societies are forced to assume due to climate change [18, 19].

Risk matrices were built to present the information obtained in a compact and clear form. In the last stage of work, contingency plans were prepared for two of the cases studied [18, 19]. The background and procedures that the National Emergencies Agency (SINAE) has implemented in conjunction with the Departmental Emergencies Coordination Centers (CECOED) were taken as a starting point, taking into account both the successful practices and the opportunities for improvement that the institutions had detected from their application [22].

3. The risk matrices used in this case study

3.1 Planning the matrices' contents

A risk matrix is a very practical technique and visual tool for analyzing and communicating information regarding the possibilities that "something", and in this case, a bridge will fail due to the intrinsic characteristics that make it vulnerable to threats, that is, what makes prone to damages due to its occurrence as well as the type and magnitude of the consequences that could be expected in case that the threat actually occurred. The matrix has a double-entry table in which vulnerability factors and danger factors are interrelated to identify and prioritize the consequences on the infrastructure that may cause different magnitudes of hydrometeorological events [7].

Vulnerability factors are those characteristics of a bridge—including its immediate environment—that make it more prone to failure. They refer to the intrinsic disposition to suffer harm. Danger factors, on the contrary, depend on hydrometeorological events rather than on the bridge. The factor that is usually considered most representative of its probability of occurrence is the return period. Thus, the methodology consists on crossing these factors and assigning them a value that reflects the probability of occurrence and the severity of events consequences. The scales to quantify probability and severity can be quantitative, qualitative, or a combination of both [7, 18].

To assemble and fill out the matrix, adequate information must be available on both the infrastructure characteristics and conditions under study and the events to be considered to identify and evaluate the resulting risks in each interaction cell. The sensitivity of this tool lies primarily in the choice of probability and severity scores given to each interaction [7, 19].

According to [23], the case study is an application that can be qualified as "*Triple baseline analysis (environmental, social and economic)*" with high-level screening. Depending on the information available, the quality of the information obtained will be determined and the list of points in which improvement is needed will be known.

In this case, the probability of occurrence has been assigned in a decreasing manner to events with a return period of 100, 200, and 500 years, while the severity of the consequences was managed according to intervals defined for each type of effect. The severity can be assigned based on experience and professional criteria: flooded area and its use, including type of crop, livestock, etc., foreseeable number of evacuees, among others. Socioeconomic criteria will also be considered, such as the characteristics of the routes that would be interrupted if a road were not passable and the economic consequences depending on the type and quantity of vehicles and freights that travel on that road [7, 18].

The impact levels considered are shown in **Table 2**, and the levels of probability of occurrence are presented in **Table 3**.

By the multiplication of the probability of occurrence and the impact severity, the results should be classified into the five classes, as defined in **Table 4**.

The results end up categorized according to the color code shown in **Table 5**, depending on the risk value [7, 18].

In the case of a bridge failure, that is to say, the bridge falling down, the vulnerability was taken as the risk value, as presented in **Table 6**; the consequences

Expected impact	Definition
Severe (3)	Impacts that could greatly affect (in quantity and severity) the community, infrastructure, and environment.
Moderate (2)	Impacts that could moderately affect (in quantity and severity) the community, infrastructure, and environment.
Low (1)	Restricted impact, with little and weak impact on the community, infrastructure, and environment.

The color code is inspired by that of a traffic light.

Table 2.
Impact levels (adapted from [7]).

Probability of occurrence	Definition
High (3)	The threat has already materialized in the location and with high frequency, or there are very strong indications of its future occurrence.
Medium (2)	The threat has manifested itself with medium frequency, or although it has not manifested itself, there are important indications of its future occurrence.
Low (1)	The threat has never materialized or has done very little, and there are no or very slight signs indicating its future occurrence.

The color code is inspired by that of a traffic light.

Table 3.
Levels of probability of occurrence (adapted from [7]).

		Impact		
		Low	**Moderate**	**Severe**
Probability	High	Moderate Risk (3–4)	Major Risk (6)	Inadmissible Risk (9)
	Medium	Tolerable Risk (2)	Moderate Risk (3–4)	Major Risk (6)
	Low	Admissible Risk (1)	Tolerable Risk (2)	Moderate Risk (3–4)

The color code is inspired by that of a traffic light.

Table 4.
Risk levels (adapted from [7]).

	Probability	1 Low; Tr = 500	2 Medium; Tr = 200	3 High; Tr = 100
Severity	1 Low	1 – Admissible	2 – Tolerable	3 – Moderate
	2 Moderate	2 – Tolerable	4 – Moderate	6 – Major
	3 Severe	3 – Moderate	6 – Major	9 - Severe

The color code is inspired by that of a traffic light.

Table 5.
Color code for risk matrices (adapted from [7]).

considered were only those related to the connection between the closest cities on both sides of the bridge and the impact on freight traffic and tourism.

3.2 Vulnerability factors

The vulnerability analysis involves considering a set of factors specific of the bridge and its circumstances (location, state of conservation, etc.), which are those that make it more prone to failure. These characteristics have been grouped according to the type and severity of the failure, for which the structure is more sensitive: factors related to the flow velocity; factors related to the occurrence of scour; and other factors that could be related to possible failure of the structure (**Table** 7) [4, 7].

The characteristics of the bridges that were finally included in the risk analysis are presented in **Table 8**. They are grouped in piles, deck and foundation characteristics, concentration of water flows, cut section, bank conditions, presence of possible obstacles, localized scour in piles or abutments, sediment accumulation, and structural status of the bridge [7].

	Low	Medium	High
Number of households affected	Up to 30	Between 30 and 100	More than 100
Number of inhabitants affected	Up to 100	Up to 300	More than 300
Services affected	No	Education	Health/Education and health
Road cut	Up to 500 m	Between 500 and 5 km	More than 5 km
Freight transport	No	Seasonal	Daily (milk products, port)
Tourism	No	Seasonal	All year
Forests, grasslands, natural fields	Up to 1 km^2	From 1 to 10 km^2	From 11 to 100 km^2
Urban and urbanized areas	Up to 0,05 km^2	From 0,05 to 0,1 km^2	More than 0,1 km^2
Dry crops and stubble	Up to 0,25 km^2	From 0,25 to 1 km^2	More than 1 km^2
Rice and stubble cultivation	Up to 0,5 km^2	From 0,5 to 5 km^2	More than 5 km^2
Beaches, dunes, fixed, and semifixed dunes	Up to 0,1 km^2	From 0,1 to 0,5 km^2	More than 0,5 km^2
Extensive crops on dairy farms	Up to 0,5 km^2	From 0,5 to 1 km^2	More than 1 km^2
Quarries, sand pits, open pit mines	Up to 0,1 km^2	From 0,1 to 0,5 km^2	More than 0,5 km^2
Horticultural zone	Up to 0,05 km^2	From 0,05 to 0,2 km^2	More than 0,2 km^2
Lost cattle	Up to 50	From 51 to 500	More than 500

Table 6.
Consequences to evaluate (adapted from [7]).

Factors related to flow velocity in the bridge section	Factors directly related to scour	Other factors related to possible failure of the structure
Span	Piles shape	Thickness of the bridge deck
Spacing between piles	Type of foundation	Structural status
Orientation related to the axis of the watercourse	State of the banks	Concentration of water flows
Location section on the watercourse	Localized scour in the piles	
Presence of singular elements that may be obstacles to flow	Localized scour in abutments	
Sediment accumulation by the bridge structure		

Table 7.
Vulnerability factors (adapted from [4]).

By using these criteria, it was obtained that almost half of the bridges in the sample were considered low vulnerability to failure, while only three were categorized as very vulnerable [7].

Parameters	Categories	Interpretation	
Piles	Piles shape	Square	These are the most unfavorable options for scour.
		Pointed	
		Circular	They are the best options for scour.
		group of cylinders	
	Number of piles	It is used together with the span to calculate the spacing between piles. If the separation is less than 10 m it is considered the highest degree of vulnerability, while if it is greater than 20 m, it will be the lowest.	
	Orientation	Perpendicular	
		skew	
Deck	Thickness	Less thickness implies greater structural vulnerability	
	span		
Type of foundations	direct	The direct foundation reduces the possibilities and magnitude of scour.	
	Pilotage		
Concentration of water flows	Yes	The concentration of flows near the bridge increases its vulnerability.	
	No		
Cut section	Straight section	Location on a straight section reduces vulnerability.	
	meander		
Bank condition	Vegetation with maintenance	Vegetated options reduce vulnerability, while bare banks increase it.	
	Vegetation without maintenance		
	bare banks		
Presence of singular elements that can result in obstacles	Yes	Free flow reduces vulnerability.	
	No		
Localized scour in the piles	Not detected	The greater the scour, the greater the vulnerability to possible structural failure.	
	moderate		
	critic		
Scour in abutments	Not detected	The greater the scour, the greater the vulnerability to possible structural failure.	
	moderate		
	critic		
Sediment accumulation by the bridge structure	visible	The presence of visible sedimentation increases the speed of passage by reducing the runoff section. This increases the vulnerability of the bridge.	
	Not visible		
Structural status	Good	If the structural condition is not good, vulnerability and the possibilities of structural failure increase.	
	Regular		

Table 8.
Considered characteristics (adapted from [7]).

3.3 Threat factors and severity of consequences

The existence of risk implies, by definition, the potential presence of danger, that is, an agent that is likely to cause harm. These agents will be of different natures and entities. To evaluate the risks, some questions must be answered, such as what could happen? When could it happen? How would it happen? What is the probability of it happening? If it happens, what would be the consequences? To do this, it is necessary to propose an analysis of the threat or danger [4, 7, 18, 19].

The threat factors are independent of the infrastructure and are linked, in this case, to hydrometeorological events. Thus, to prepare a list of threat factors, it is useful to understand danger as the probability of a harmful phenomenon occurring of a certain intensity, during a certain period of time, which will depend on the physical-geographical characteristics of the place. It is important to have enough information about the recent, historical, and projected climate in the study area. When it is possible, historical infrastructure responses to climate change will be also considered (PIEVC, 2011 as referred in [5]).

In the case of floods, it is necessary to obtain reliable data on the physical characteristics of the affected area and its population (size, distribution, density, economic and cultural characteristics, education, health coverage, among others) [7]. The effects of the storms studied refer to the destruction of physical assets (damage) and the alteration of economic flows (losses and additional costs). Consequently, it is necessary to know in the most quantitative way possible the previous situation—in general through quantitative information published by official sources or documents based on them—as well as the damages, losses, and additional costs caused by these disasters, in order to be able to carry out a quantification of its costs and impacts as precise as possible. As the study aims to quantify the greatest possible number of aspects of interest, it is proposed to quantify parameters of each bridge and its immediate environment before and after the occurrence of the adverse hydrometeorological event being studied and to attempt to quantitatively assess the impact, based on the differences between both conditions. It also includes an economic quantification [7, 18, 19].

The main consequences could be that the deck height of non-submersible bridges is exceeded, that submersible bridges remain out of service for longer than considered in their design; the increase of localized erosion in piles and abutments, and that the structure fails as a consequence of one or more of the aforementioned effects. Likewise, considering the bridge integrated into its closest environment, the severity of other consequences related to floods and, consequently, the losses generated due to the dangerous event must also be taken into account [7, 18].

It is also necessary to consider the severity of the effects of losing road connectivity. The latter is related to the type of load transported on that section of the route, the proximity to ports and national borders, the towns it connects and the services that each one has, the existence of alternative connection options with other towns during traffic interruption, among others. The evaluated consequences, which are classified according to their severity, are listed in **Table 6**, with the categories considered in each case [7, 18].

Other factors that were taken into account when assessing the severity of the consequences are the greater or lesser interdependence of the localities closest to either side of the bridge (high vulnerability was considered when the population of one of them was more than triple the population of the other), the annual average daily traffic (less than 500 vehicles was considered a low level of traffic while more than 2000 was considered high), and the proximity to borders and ports (more weight was given to the proximity to the ports of Montevideo and Nueva Palmira, and in second place, the dry borders and binational bridges) [7, 18].

The threats or dangers considered were hydrometeorological events with different return periods: 100, 200, and 500 years, and the structural failure of the bridge [7].

3.4 Applications

The risk matrices corresponding to each of the considered bridges are included in [7]. Two of the main cases are also discussed in more detail in [18]. These two cases have been chosen to be presented in this chapter. The first case refers to a bridge on National Route 18, located near the entrance to the town of Vergara, in the east of the country, and the other one is the bridge over Arroyo Colla on National Route 2. The expected impact levels matrixes and the subsequent risk matrixes are presented in **Tables 9–12**.

3.4.1 Route 18: entrance bridge to Vergara town

The entrance to Vergara town is an old bridge over Arroyo Parao. Its location is sketched on a map of Uruguay in **Figure 1(a)**. The town has another entrance, the bridge on Route 91; it is also close to International Route 8, one of the most active land freight transportation routes in Uruguay.

	Road interruption during less than 72 h*	**Long-term road interruption**	**Failure**
		(Tr = 100, 200 y 500 years)	
Number of households affected in Vergara town	Less than 30	Between 30 and 100	Between 30 and 100
Number of inhabitants affected in Vergara town	Less than 100	Less than 100	Between 100 and 300
Affected services	No	No	No
Interruption Road 18	Moderate	Moderate	Severe
Interruption Route 91	Moderate	Moderate	Moderate
Interruption Road 8	Low	Low	Low
Transport of freights	Moderate	Severe	Severe
Forest, grasslands, natural fields	Moderate	Moderate	Moderate
Urban and urbanized areas	Moderate	Severe	Severe
Dry crops and stubble	Low	Low	Low
Rice and stubble culture	Moderate	Moderate	Severe
Lost cattle	Moderate	More than 3000	More than 3000

This type of event occurs for Tr less than 100 years. The color code is inspired by that of a traffic light.

Table 9.
Expected impact levels for Route 18 (adapted from [18]).

		Impact		
		Low	**Moderate**	**Severe**
Probability	HIGH Road interruption of low permanence	Moderate Risk (3): Affected households in Vergara/Affected inhabitants in Vergara/ Affected services/Road 8 interruption/Dry crops and stubble	Major Elevado (6): Road 18 interruption/Road 91 interruption/Freight interruption/Forest, grasslands, natural fields/ Urban and urbanized areas/Rice and stubble culture/Lost cattle	Inadmissible Risk (9): Not detected
	MEDIUM Road interruption longer than 72 h	Tolerable Risk (2): Affected inhabitants in Vergara/Affected services/Road 8 interruption/Dry crops and stubble	Moderate Risk (4): Affected households in Vergara/Road 18 interruption/Road 91 interruption/Forest, grasslands, natural fields/Rice and stubble culture	Major Risk (6): Freight transport/Urban and urbanized areas/Lost cattle
	LOW Failure/ collapse of the bridge	Admissible Risk (1): Affected services/Road 8 interruption/Dry crops and stubble	Tolerable Risk (2): Affected households in Vergara/Affected inhabitants in Vergara/ Road 91 interruption/ Forest, grasslands, natural fields	Moderate Risk (3): Road 18 interruption/Freight transport/Urban and urbanized areas/Rice and stubble culture/Lost cattle

The color code is inspired by that of a traffic light.

Table 10.
Risk matrix for Route 18 (adapted from [18]).

The damage and losses associated with the 100-year return period flood are not very different from those with 200-year and 500-year return periods. The difference focuses on a short-term or long-term interruption of the route by the flood.

The short-term interruption of the route affects 27 households and 86 inhabitants; the long-term interruption affects 38 households and 122 inhabitants. The estimated costs of these damages are approximately US$ 1.249.000 and US$ 1.740.230, respectively. The costs of evacuating people and transitional housing are US$ 18.600 and US $ 22.600 more in each case.

No educational or health services are expected to be affected.

Freight transport is expected to be affected moderately and severely, respectively; approximately, 20.500 tons cannot reach their destination on time. In the worst case, they have an estimated cost of US$ 1.320.000.

Large areas of rice culture are expected to be affected: 6,7 km^2 in the short-term flood and 10,1 km^2 in the long-term one. In both cases, only small areas of dryland crops are expected to be affected. The estimated costs are approximately US$ 1.052.000 and US$ 1.577.000, respectively.

The loss of livestock is the last major cost to be considered: more than 3100 heads of cattle or US$ 3.845.000 in the first case and more than 3530 heads of cattle or US$ 4.378.500 in the second one.

The estimated cost of managing a short-term flood is approximately US$ 7.450.000, including damage and losses; in the case of a long-term flood, it is about US $ 9.100.000.

	Road interruption during less than 72 h*	Long-term road interruption	Failure
		(Tr = 100, 200 and 500 years)	
Number of affected households in Rosario city	More than 100	More than 100	More than 100
Number of affected inhabitants in Rosario city	Variable	More than 300	More than 300
Affected services	No	No	No
Road 2 interruption	Moderate	Moderate	Severe
Road 1 interruption	Moderate	Moderate	Moderate
Road 61 interruption	Low	Low	Moderate
Road 52 interruption	Low	Low	Moderate
Freight transport	Low	Moderate	Severe
Tourism	Low	Low	Moderate
Forests, grasslands, natural fields	Moderate	Moderate	Moderate
Urban and urbanized areas	Moderate	Moderate	Moderate
Dry crops and stubble	Low	Low	Low
Beaches, dunes, fixed and semifixed dunes	No	No	No
Extensive drops on dairy farms	No	No	No
Lost cattle	Moderate	More than 400	More than 600

**This type of event occurs for Tr less than 100 years. The color code is inspired by that of a traffic light.*

Table 11.
Expected impact levels for Route 2 (adapted from [18]).

The information on **Table 9** is used to complete the cells of **Table 10**, considering the situations in **Table 5**: high probability of occurrence and severe impacts are not admissible, while low probability of occurrence and low severity of impacts are admissible; and all intermediate ratings as shown in **Table 5**.

As a result, no inadmissible risk situations are detected, but many major and moderate risk situations have been identified as well as others of tolerable and admissible risk.

3.4.2 Bridge over arroyo Colla

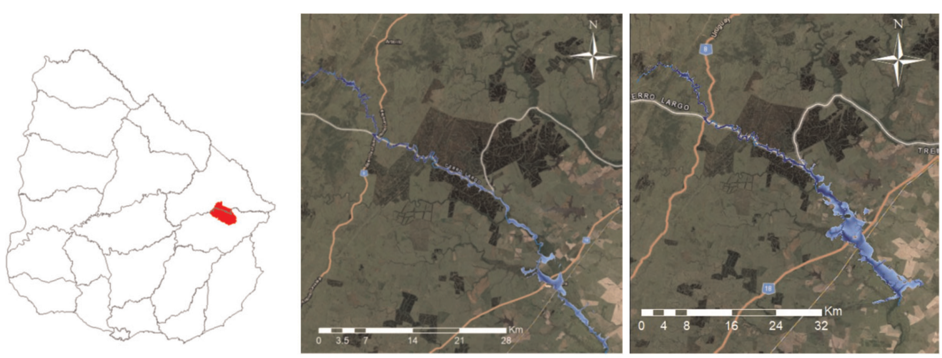
The bridge over Arroyo Colla was built in 1917. Its location is sketched on a map of Uruguay in **Figure 2(a)**. It is close to Rosario town, in the department of Colonia. The town is also close to other routes: International Route 1, which connects Montevideo with the city of Colonia and with Buenos Aires (Argentina) through its international passenger port; and National Routes 52 and 61, which connect Rosario with nearby productive areas (crops, livestock, dairy farms).

This case is similar to the previous one: the damage and losses associated with the 100-year return period flood are not very different from those with 200-year and 500-

		Impact		
		Low	**Moderate**	**Severe**
Probability	HIGH Road interruption of low permanence	Moderate Risk (3): Affected services/Road 61 interruption/Road 52 interruption/Freight transport/Tourism/Dry crops and stubble/ Beaches/Extensive crops on dairy farms	Major Risk (6): Affected inhabitants in Rosario city/Affected households in Rosario city/Road 1 interruption/Road 2 interruption/Grasslands/ Urban areas/Lost cattle	Inadmissible Risk (9): Not identified
	MEDIUM Road interruption longer than 72 h	Tolerable Risk (2): Affected services/Road 61 interruption/Road 52 interruption/Tourism/ Dry crops and stubble/ Beaches/Extensive crops on dairy farms	Moderate Risk (4): Affected households in Rosario city/Road 1 interruption/Road 2 interruption/Freight transport/Grasslands/ Urban areas	Major Risk (6): Affected inhabitants in Rosario city/Lost cattle
	LOW Failure/ collapse of the bridge	Admissible Risk (1): Affected service/Dry crops and stubble/ Beaches/Extensive crops on dairy farms	Tolerable Risk (2): Affected households in Rosario city/Road 1 interruption/Road 61 interruption/Road 52 interruption/Tourism/ Grasslands/Urban areas	Moderate Risk (3): Affected inhabitants in Rosario city/Road 2 interruption/Freight transport/Lost cattle

The color code is according to that of Table 5. The color code is inspired by that of a traffic light.

Table 12.
Risk matrix for Route 2 (adapted from [18]).



(a) (b) (c)

Figure 1.
(a) Location of Vergara town and its entrance bridge. (b) Affected zone in first 24 hours of flooding. (c) Affected zone for Tr = 500 years (from [7]).

year return periods. The most important thing is the permanence of the interruption of the route due to the flood.

The short-term interruption of the route affects 105 households and 336 inhabitants; the long-term interruption affects 123 households and 394 inhabitants. The estimated costs of these damages are approximately US$ 7.248.000 and US$ 8.568.000, respectively. The costs of evacuating people and transitional housing are US$ 61.000 and US$ 62.700 more in each case.

(a) (b) (c)

Figure 2.
(a) Location of the bridge over Arroyo Colla. (b) Affected zone in first 24 hours of flooding. (c) Affected zone for Tr = 500 years (from [7]).

Also in this case, no educational or health services are expected to be affected.

Freight transport is expected to be affected, moderately and severely respectively; approximately, 16.300 tons cannot reach their destination (e.g., Nueva Palmira International Port) on time. Given that it is an international port that there are more sensitive merchandise involved and also that the tourist connection through the port of Colonia may be affected; the losses are estimated at US$ 6.250.000.

Dryland crops areas are expected to be affected: 1,5 km^2 in the short-term flood and 1,75 km^2 in the long-term one. The estimated losses are approximately US$ 93.000 and US$ 108.000, respectively.

The loss of livestock is the last cost to be considered: 430 heads of cattle or US$ 2.304.000 in the first case and more than 650 heads of cattle or US$ 2.504.700 in the second one.

The estimated cost of managing a short-term flood is approximately US$ 16.000.000, including damage and losses; in the case of a long-term flood, it is about US$ 17.600.000. These high figures are mainly related to the large urban areas affected by the flood and the interruption of freight transportation to the Nueva Palmira International Port, the second cargo port in Uruguay.

In the same way, as the previous case, the information on **Table 11** is used to fill in the cells of **Table 12**, considering the cases in **Table 5**.

No inadmissible risk situations are detected, but many major and moderate risk situations have been identified as well as others of tolerable and admissible risk.

4. Conclusions

Successful adaptation to climate change is based on a multidimensional perspective that encompasses social, economic, environmental, and institutional aspects. Therefore, risk and vulnerability assessments intended to inform these adaptation strategies also require a multidimensional perspective.

An integrated and interdisciplinary approach makes it possible to greater certainty when addressing the complexity and dynamics of social and environmental systems and contribute to more effective risk management by the different actors involved in making decisions on risk reduction or adaptation.

Simple but effective elements, such as William Fine's risk analysis matrix adapted to the case study, may produce extremely effective results in the synthesis, assessment, and communication of information.

Acknowledgements

The authors thank the Ministry of Transportation and Public Works for financing the project through an agreement with the Julio Ricaldoni Foundation of the Faculty of Engineering, UdelaR, and for authorizing the publication of this work.

They also sincerely thank all the members of the Climate Change Road Resilience Group, the inter-institutional team that carried out this project: Arch. Rafael Ferrando, Mag. Eng. Hebenor Bermúdez, Mag. Eng. Gabriela Acosta† from MTOP; and Eng. Malena López Parard, Eng. Micaela Luzardo Rivero and Eng. Juan Ignacio Pais from DIA-IMFIA (FING-UdelaR).

Conflict of interest

The authors declare no conflict of interest.

Author details

Alice Elizabeth González[1]*, Martín Paz Urban[2], Martín Goyeneche[2] and Lady Carolina Ramírez[1]

1 Faculty of Engineering, Department of Environmental Engineering-IMFIA, University of the Republic (Udelar), Montevideo, Uruguay

2 National Administration of Highways, Ministry of Transportation and Public Works, Montevideo, Uruguay

*Address all correspondence to: elizabet@fing.edu.uy

References

[1] Renssnature & Consulting Cía. Ltda. Capítulo X Análisis de Riesgos (para Petroamazonas). Ecuador: Gruporenss; 2016. p. 2016

[2] Dirección General de Alianzas Público Privadas DGAPP. Metodología de Análisis de Riesgo. República Dominicana: DGAPP; 2020

[3] Cardona OD, van Aalst MK, Birkmann J, Fordham M, McGregor G, Perez R, et al. Determinants of risk: Exposure and vulnerability. In: Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation. A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change (IPCC). Cambridge, UK, and New York, NY, USA: Cambridge University Press; 2012. pp. 65-108

[4] Grupo Resiliencia Vial al Cambio Climático. Informe: Fase I. MTOP - FJR. Montevideo, Uruguay: Grupo Resiliencia Vial al Cambio Climático; 2019. 23 p

[5] Sandink D, Lapp D. The PIEVC protocol for assessing public infrastructure vulnerability to climate change impacts: National and international application. In: CSCE 2021 Annual Conference, Canada. May 2021

[6] Engineers Canada/Ingénieurs Canadá. Public Guideline on Risk Management. Canadá: Engineers Canadá; 2020

[7] Grupo Resiliencia Vial al Cambio Climático. Producto 2: Análisis de detalle de veinte puentes. MTOP - FJR. Montevideo, Uruguay: Grupo Resiliencia Vial al Cambio Climático; 2020. 143 p

[8] Silveira L, Genta JL, Charbonnier F, Failache N, y Alonso, J. Directivas de diseño hidrológico – hidráulico de alcantarillas. Uruguay: Universidad de la República, Facultad de Ingeniería, IMFIA; Ministerio de Transporte y Obras Públicas, Dirección Nacional de Vialidad; 2000

[9] Unión Europea. Directiva 2007/60/CE del Parlamento Europeo y del Consejo, de 23 de octubre de 2007, relativa a la evaluación y gestión de los riesgos de inundación. Belgium; 2007

[10] Nixon S, Horn J, Hödl-Kreuzbauer E, ter Harmsel A, Dominique VE, Thomas D. European Overview Assessment of Member States' Reports on Preliminary Flood Risk Assessment and Identification of Areas of Potentially Significant Flood Risk. Luxembourg: Publications Office of the European Union; 2016. DOI: 10.2779/576456

[11] European Commission DG. Science for Environment Policy: Responding to Floods in Europe: New Framework Assesses Effectiveness of Flood Emergency Management Systems Environment News Alert Service, Edited by SCU. Bristol: The University of the West of England; 2017

[12] Gilissen HK, Alexander M, Matczak P, Pettersson M, Bruzzone S. A framework for evaluating the effectiveness of flood emergency management systems in Europe. Ecology and Society. 2016;**21**(4):27. DOI: 10.5751/ES-08723-210427

[13] Veleda S, Martínez-Graña A, Santos-Francés F, Sánchez-San Roman J, Criado, M. Analysis of the hazard, vulnerability, and exposure to the risk of flooding

(Alba de Yeltes, Salamanca, Spain). Applied Sciences. 2017;**7**(2):157. DOI: 10.3390/app7020157

[14] UNIR Revista. 2023. El método William T. Fine para el análisis de riesgos laborales - 26/12/2023. Available from: https://www.unir.net/ingenieria/revista/metodo-william-t-fine/

[15] Belloví B, Malagón P. NTP 330: Sistema simplificado de evaluación de riesgos de accidente. España: Instituto Nacional de Seguridad e Higiene en el Trabajo, Centro Nacional de Condiciones de Trabajo, Ministerio de Trabajo y Asuntos Sociales; s.f

[16] Universidad Nacional de Litoral UNL (s.f.). Diagnóstico Situacional - Control de Riesgos. Available from: http://www.eis.unl.edu.ar/z/adjuntos/2994/Control_de_Riesgos.pdf

[17] Qué es el método de evaluación W. Fine. Available from: https://seguridadindustrial77.blogspot.com/2017/11/metodo-de-evaluacion-w-fine.html

[18] Grupo Resiliencia Vial al Cambio Climático. Producto 3: Planes de Contingencia. MTOP - FJR. Montevideo, Uruguay: Grupo Resiliencia Vial al Cambio Climático; 2020. 67 p

[19] González-Fernández AE, Paz-Urban M, Goyeneche M. Análisis de vulnerabilidad de obras viales en Uruguay ante el cambio climático. Quivera Revista de Estudios Territoriales. 2022;**24**(2):5-27. DOI: 10.36677/qret.v24i2.19349

[20] US Army Corps of Engineers, Hydrologic Engineering Center. HEC-RAS River Analysis System. User's Manual, Version 5.0. USA: US Army Corps of Engineers, Hydrologic Engineering Center; 2016

[21] Papaioannou, G., Loukas, A. y Vasiliades, L. (2019). Flood risk management methodology for lakes and adjacent areas: The Lake Pamvotida paradigm. Proceedings, 7 (21), doi: 10.3390$/$ECWS-3-05825

[22] SINAE. Informes de consultorías Generación de conocimientos en Gestión Integral del Riesgo. Guía. 2014;**6**:211-226

[23] PIEVC Global Partnership. PIEVC© Family of Resources Catalogue. A Guide for Selecting Climate Risk Assessment Methods, Data, and Supporting Materials. Canadá: Public Infrastructure Engineering Vulnerability Committee PIEVC; 2021