ADAPTING ROAD INFRASTRUCTURE TO CLIMATE CHANGE: INNOVATIVE APPROACHES AND TOOLS

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ABSTRACT

Extreme climate events have major direct impacts on all road infrastructures. The consequences are mainly economic, but also concern safety. Climate change considerably modifies infrastructure's vulnerability to these impacts. Usually, infrastructure is designed on the basis of regulations and calculation codes which supply typical intensity values for climatic phenomena associated with a return frequency (e.g. a 10 year rainfall or a 100 year flood). While this reference event concept, based on return frequency, has been extremely useful in the past, it is becoming dangerous insofar as the underlying assumption that the climate of tomorrow will be similar to that of yesterday is no longer correct.

Despite persistent scientific uncertainties with regard to climate change issues, the cost of "inaction" clearly demonstrates the essential need to act now and in a relevant manner. Concrete and effective solutions are currently made available to road owners and operators.

The present paper aims to present several outstanding initiatives, from upstream institutional approaches to real-time risk management, stemming from national and international research undertaken in recent years, local implementations with infrastructure owners, and international networking.

Key words: climate change, adaptation, infrastructure, risk, vulnerability, impact, uncertainty, method, tool

1. RATIONALE

Extreme climate events have major direct impacts on transport infrastructure. The consequences are mainly economic, but also concern health and safety. In 2005, Hurricane Katrina provided a sad example of this in the USA. In France, the destruction or interruption of roadway routes are not infrequent (see Figure 1), as is the case for breaks in electric power lines. The two storms that took place in 1999 have left their mark, as well as the consequences of the 2003 heat wave in regard to the dramatic increase in the elderly mortality rate.

According to the National Observatory of the Effects of Global Warming (ONERC), extreme meteorological phenomena will increase in number and degree in the years to come in France [1]. Northern European countries already experience significant consequences of climate change. It has been acknowledged that "Road authorities need to evaluate the effect of climate change on the road network and take remedial action concerning design, construction and maintenance of the road network" (Era-Net Road, 2008) [2]. Despite persistent scientific uncertainties, the cost of "inaction" clearly demonstrates the essential need to act now and in a relevant manner [3].

Figure 1 - 04 December 2003, inundation of the Rhône river valley in South of France. The A54 motorway was flooded during 11 days.

Transport infrastructure is usually very vulnerable to climate events significantly stronger than their design level, while it is often much less vulnerable to variations of average values of temperature, rainfall or wind. The infrastructure is designed on the basis of regulations and calculation codes which supply typical intensity data for climatic phenomena (wind speed, rainfall, snow depth, temperature variations, etc.), associated with a return frequency (ten-year rainfall, hundred-year flood, etc). These intensities - and frequencies - have been defined from meteorological phenomena experienced in the past, and are readjusted according to recorded changes. While this reference event concept, based on return frequency, has been extremely useful in the past, it is becoming dangerous insofar as the underlying assumption that the climate of tomorrow will be similar to that of yesterday has become totally incorrect. Certain calculation rules may no longer fit satisfactorily with the increased climatic variability forecast for the future. While we have to design engineering structures with lifetimes of one hundred years or more, this is precisely the period during which climate change is expected to be particularly strong.

Transport infrastructure operators have observed an increase in social intolerance to hazards (whether of climatic or other nature) over the years. The growing requirements of the user-citizen-consumer, and the expanding judiciarization of our society can be seen as two additional factors making new approaches by the concerned authorities essential regarding the vulnerability of the networks they are in charge of. It is now established public knowledge that inevitable climate change is in process. This will tend to considerably weaken the position, in the event of future litigation, of any stakeholder in a position of responsibility who acts (or, above all, who fails to act) as if he was totally unaware of the situation. Furthermore, the notion of reference or dimensioning event must not lead to loss of control of the situation when the reference or dimensioning parameters are exceeded. This has become less and less tolerable, and increasingly difficult to sustain in social terms. On the other hand, as budgets are not infinitely extensible, it is impossible to build an infrastructure capable of withstanding any climatic hazard. The only reasonable way to reconcile these constraints is to express the problems in terms of risk, and to address them by means of a multi-party analytical process. It is all the more essential as climatic phenomena will be increasingly characterised by occurrence and intensity probabilities more complex to define than the past statistical data. The increasing constraints to which public budgets are subject must not be an indirect reason for adopting a wait-and-see position. The new public-private partnerships provide an example of how to involve new innovative forces in the transport sector.

In this context, a wide range of methodological approaches and tools have been developed, aiming to assist transport infrastructure stakeholders in managing extreme climate events and climate change. This experience is made available, from upstream institutional approach to real-time risk management, through the following sections.

2. ASSESSING TRANSPORT SECTOR PREPAREDNESS TO CLIMATE CHANGE

Climate change adaptation is an emerging issue, even in developed countries. Only a few countries are currently getting involved, and it is still a research area. Some national policies and strategies have been drawn up (see Potential Impacts of Climate Change on U.S. Transportation, 2008) [4], but only a few methodological or technical approaches have been launched (see Climate Change Adaptation Strategy, UK Highways Agency, 2009) [5].

Countries in the Middle East and North African region are likely to be severely impacted by climate change. Indeed, climate models forecast a more frequent occurrence of extreme climate events involving torrential rains and storm conditions. In the transport sector, in particular, these events could have dramatic consequences on infrastructure, for example through flooding, erosion (see photo below), the destruction of embankments, protection works, viaducts and bridges. Few countries in the developing world have begun to tackle these issues.

Figure 2 - Destruction of a provincial road by a flash flood in the Atlas Mountains (Morocco, 2006)

In 2008, a “Pilot Study on Adaptation to Climate Change in the Transport Sector” in Morocco, has been conducted by the World Bank [6]. This pilot study was an attempt to increase awareness on this issue in emerging countries. A risk assessment approach was implemented in three successive steps: risk analysis, risk management and definition of adaptation measures.

1. On the basis of available information (especially meteorological forecasts in the long run), and using two case studies, a typology of extreme climate events affecting the road and railway sectors (and of their potential impacts) were defined. The most important vulnerabilities regarding extreme climate events on the selected transport infrastructure were identified. The potential impacts with respect to maintenance and operation of the infrastructure were described. Rough evaluations of the costs that may result from extreme climate events were provided.

2. Interviews with the Moroccan authorities made it possible to assess the understanding, knowledge and interest of the issues related to adaptation to climate change in the transport sector. In the meantime, all available information on vulnerabilities in the road and railway sectors in Morocco, the impact of extreme climate events on road and rail infrastructure as well as on transport services, and the possible adaptation measures were collected, reviewed and assessed.

3. Lastly, the study described a set of preventive and operational measures: improve knowledge and develop decision-making tools; inventory critical points of the transportation network regarding climate risks; change construction standards, especially concerning hydraulic works; implement risk analysis and cost-benefit analysis in the decision-making process of major investments; anticipate and manage extreme events with specific methods and tools (see RIMAROCC and GERICI); define and schedule programmes for reconstruction or retrofitting key infrastructure likely to be affected by climate change; and strengthen the institutional framework.

3. ASSESSING HYDRO-METEOROLOGICAL ISSUES WHEN DESIGNING TRANSPORT INFRASTRUCTURE

The following case study on the evaluation of the El-Niño phenomenon on the coastal road network in Peru can be considered as one of the first applied studies on climate change adaptation. It was conducted in 1999, in the framework of the programme launched by the Peruvian Government on IBRD/IDB financing [7].

The El-Niño phenomenon causes terrible damage to the coastal area of Peru and particularly impacts on the country road infrastructure. In 1983, an El-Niño episode (frequency estimated at 50 years) destroyed a large number of bridges. These were all rebuilt using the same dimensioning models as before. In 1997-98, a new El-Niño episode, as severe as that of 1983, had the same impact on the same structures (see Figure 3).

Figure 3 - Large bridge destroyed by an El-Niño episode in 1998

The purpose of the study was to analyse the correlation between the El-Niño phenomenon and the regional hydro-meteorology in order to set up a global prevention strategy against events similar to the 1997-98 El-Niño. The methodological approach included two stages: (i) Evaluation of the extent and frequency of floods resulting from the El-Niño phenomenon, on the basis of new hydro-meteorological parameters; (ii) setting up, on a regional scale, a global forecasting strategy. The main methodological steps can be summarised as follows:

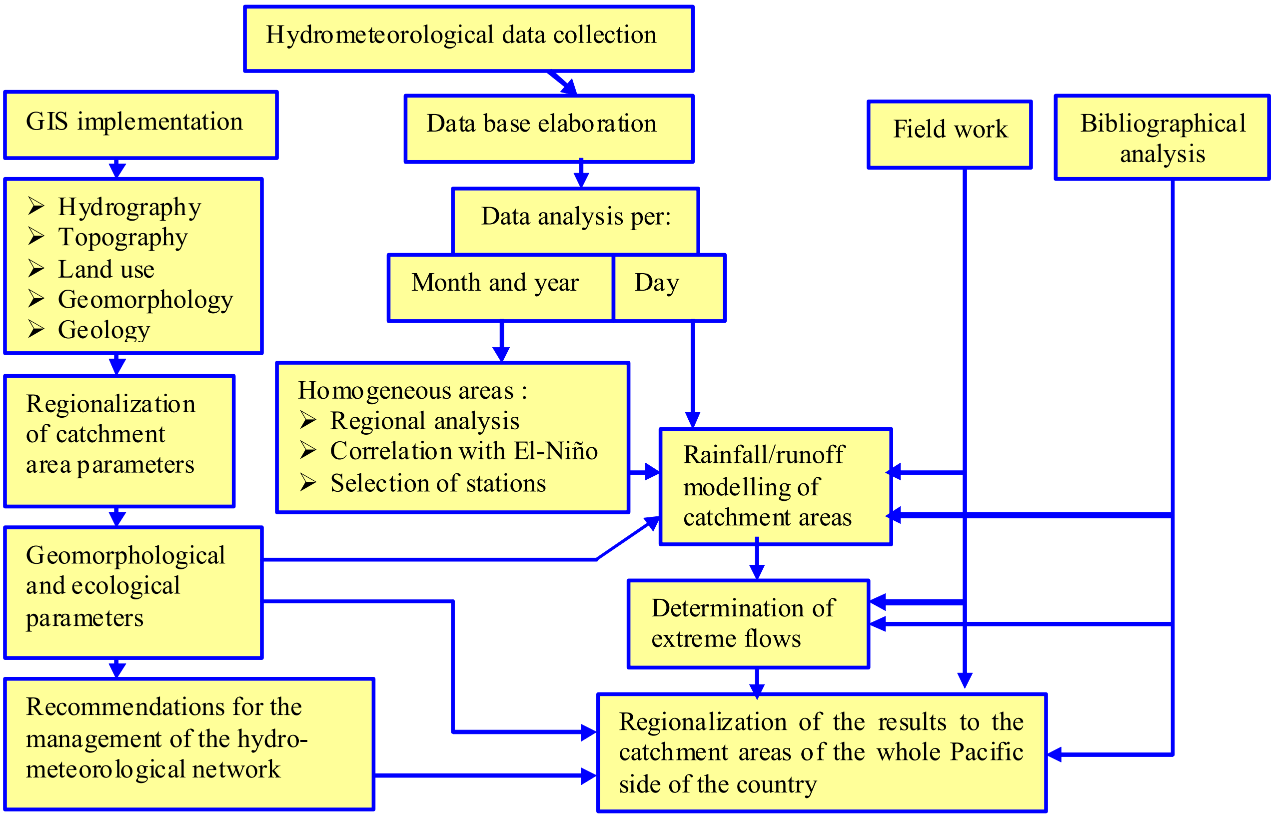

Figure 4 - Methodological steps of the evaluation of the El-Niño phenomenon on the coastal road network in Peru

Recommendations were provided to adapt transport infrastructure. For example, instead of reconstructing expensive bridges with high uncertainties regarding their lifespan, in certain critical locations it was decided to build submersible fords and fuse structures in the case of strong El-Niño action, the infrastructure being open normally to traffic the rest of the time. The study demonstrates that an error in the understanding of the nature of changes in climatic phenomena can have extremely costly consequences while simple and cheap solutions may exist.

4. MANAGING CLIMATE CHANGE RISKS FOR TRANSPORT INFRASTRUCTURE

Adaptation to the changing conditions must be based on an evaluation of the risks and of the different strategies that can be chosen. Thus there is a need for a systematic method that can help to structure the risks and evaluate the cost-benefit outcome of different actions. This was the aim of the RIMAROCC project, launched in 2008 [8]. RIMAROCC (Risk Management for Roads in a Changing Climate) is a common European methodological approach, funded by 11 National Road Administrations, through the ERA-NET Road research programme (6th Framework Programme of the EC).

The RIMAROCC method is designed to be general and to meet the common needs of road owners and road administrators in Europe. The method seeks to present a framework and an overall approach to adaptation to climate change. The method is based on existing risk analysis and risk management tools for roads within the ERA-NET Road member states and others. Work dealing with risk analysis and climate change is taking place in many countries. The proposed method is designed to be compatible and function in parallel with existing methods, allowing specific and functional methods for data collection, calculations and co-operation within each organisation to be maintained. The method is also in line with the ISO 31 000 standard on risk management.

In order to develop the RIMAROCC method, several activities have been carried out. First, critical climate factors were identified through a bibliographical review and workshops with climate experts. Then, several existing risk management methods were discussed among project members, road owners and ERA-NET ROAD contact persons. Last, risk criteria and indicators were established. From the results of these activities the RIMAROCC framework was drafted, and then tested in several case studies in France, Norway, Sweden and the Netherlands, at various geographical scales: structural (e.g. a bridge), section (e.g. a 20-50 km long motorway section), network (e.g. 100-1000 km network of primary roads) and area (e.g. a regional territory) level.

The proposed method is a cyclic process to continuously improve the performance and capitalise on the experiences. It 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 for the road organisation. In practice the steps are not always totally separated. There can be work going on in several steps at the same time – but it is very important that the logic structure is kept. There are feedback loops from each step to the previous ones and also a marked loop from the last step as a reflection and as part of the cyclic process (see Figure 5).

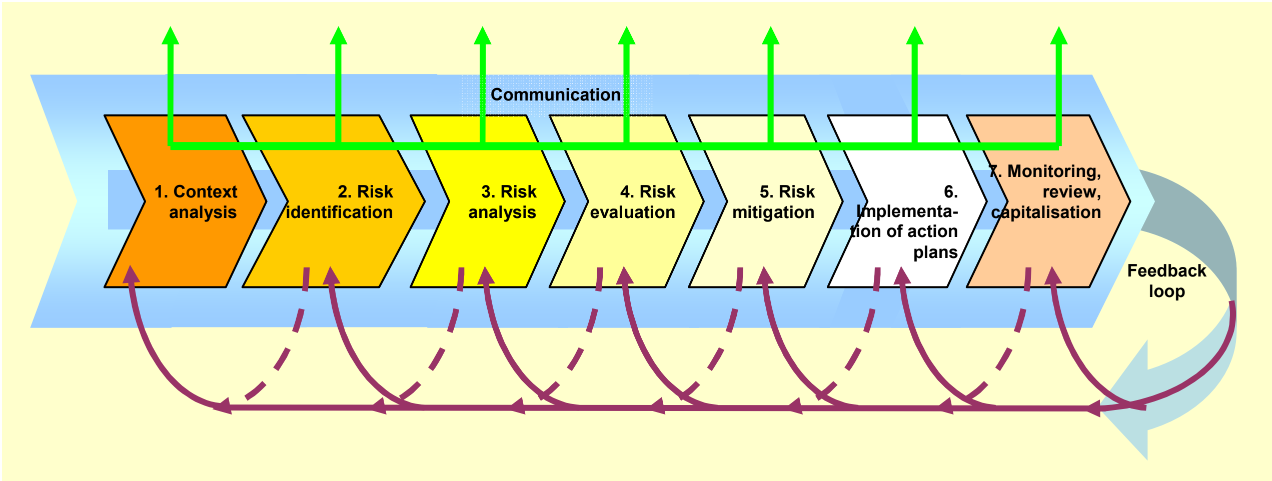

Figure 5 - The Framework of the RIMAROCC method of risk management for roads in a changing climate.

The permanent communication with stakeholders, external experts and others is very important and marked as (green) arrows throughout the whole process. An outline of the specific sub-steps is shown in Table 1.

Table 1 - Key steps and sub-steps of the RIMAROCC risk management method.

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 capitalise	7.1 Regular monitoring and review 7.2 Re-plan in the event of new data or a delay in implementation 7.3 Capitalisation on return of experience of both climatic events and progress of implementation
Communication and gathering of information	

5. IDENTIFYING TRANSPORT INFRASTRUCTURE VULNERABILITIES TO CLIMATE CHANGE

The RGCU (Civil Engineering and Urban National Network), with co-financing from the French Ministry of Public Works, has launched a research programme (in 2003) on the impacts of climate change on transport infrastructure. The main outcome of the programme was the elaboration in 2007 of a specific tool, named GERICI (Risk Management related to Climate Change for Infrastructure) developed for infrastructure owners and operators [9].

Using a risk analysis approach, GERICI has developed a GIS model for measuring the vulnerability of all sensitive components of an infrastructure (motorway in this case, but transposable to other linear transport infrastructure). The risk analysis method used in GERICI is a combination of several existing approaches described in PIARC publications, or the FMECA (Failure Modes, Effects and Criticality Analysis) method. It has applied lessons learnt from risk management in highly sensitive domains such as the nuclear industry.

The systemic approach implemented in GERICI highlights the links between the elements structuring danger and risk issues. It has made it possible to model hazard in more general terms, as a process chain leading a source of danger to trigger disastrous effects on infrastructure, users, residents, the environment, etc. The following diagram shows the main GERICI steps: the green boxes are general aspects; the blue ones are specific to the infrastructure owner.

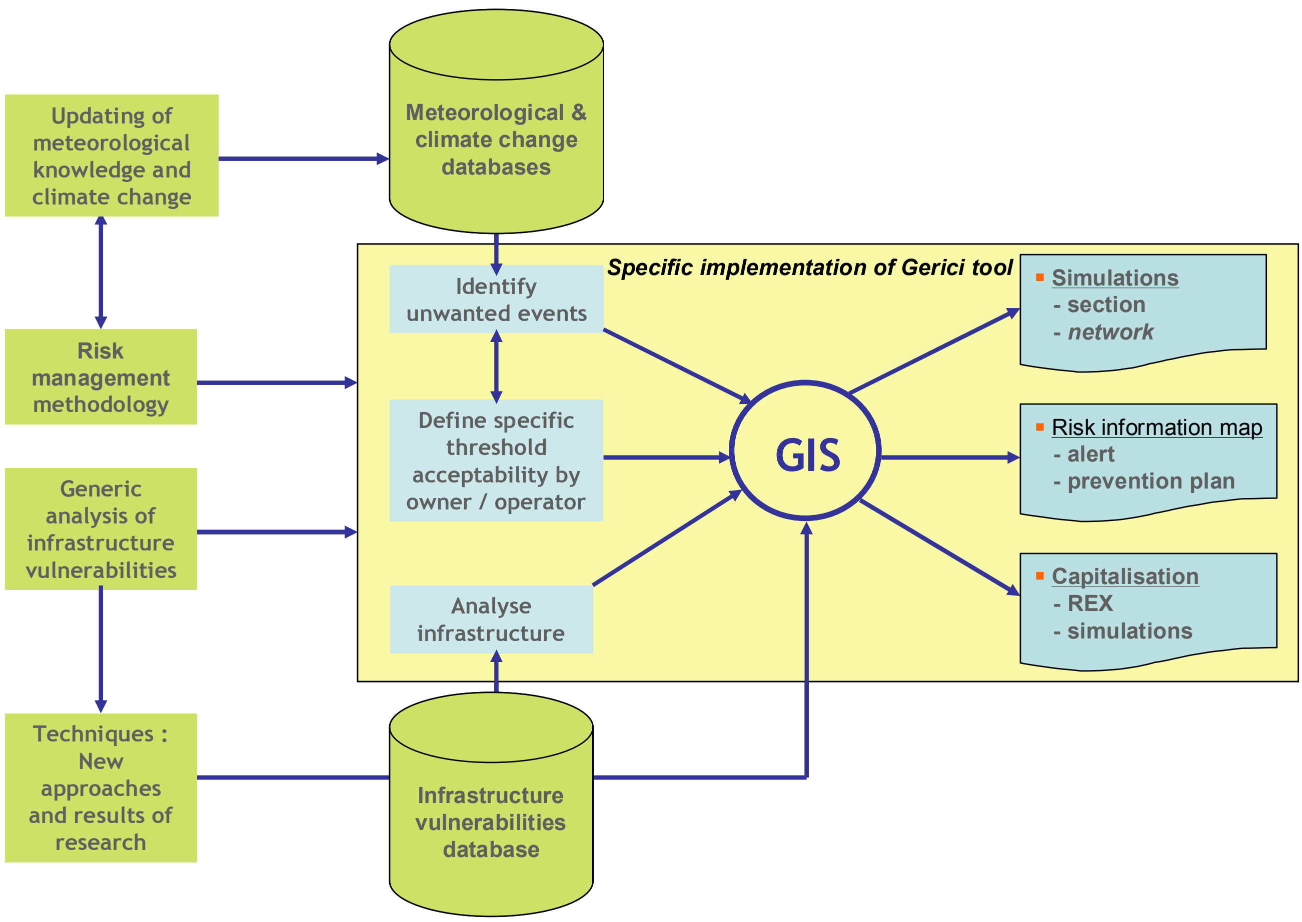

Figure 6 - The GERICI methodological approach

GERICI can be used in two ways. In simulation mode, the tool can be used to identify vulnerable sections and objects thereby making it possible to take preventive action on a priority basis (see Figure 7). When an extreme weather alert is issued by a meteorological institute, the GIS tool can be used to measure the probable consequences for the infrastructure and to provide instructions and decision scenarios for operators (see Figure 8).

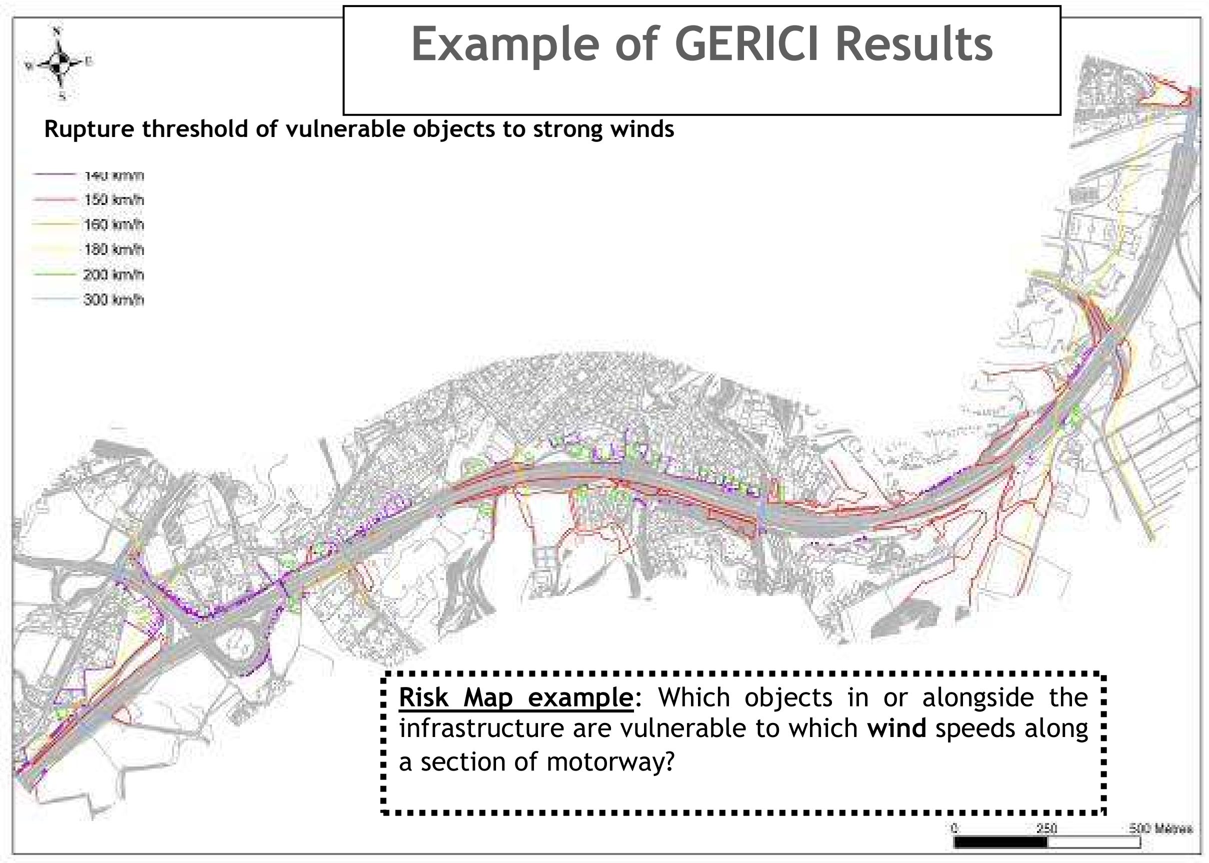

Figure 7 - A GERICI application: vulnerability of transport infrastructures to strong winds

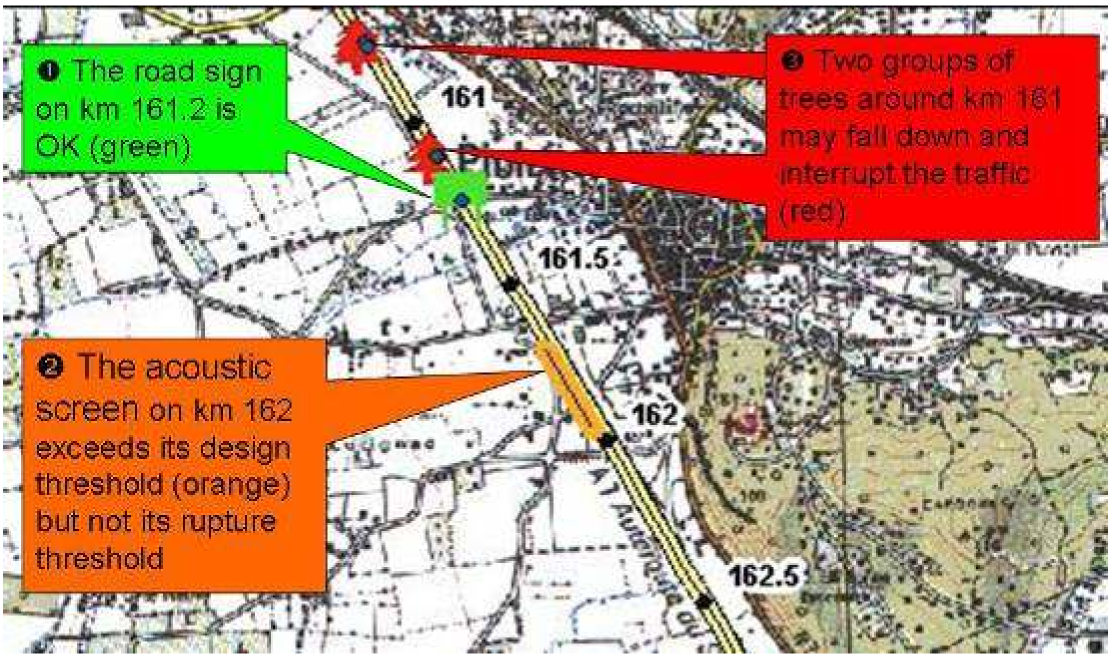

Figure 8 - A GERICI application: simulation of a 160 km/h wind

An expertise has progressively emerged from these analyses, for assessing the vulnerability of a route and then a complete network. GERICI remains the only tool of this kind on the international scene and its approach has been used as the main reference for the elaboration of the RIMAROCC project.

6. FORECASTING AND MANAGING EXTREME CLIMATE EVENTS IN REAL TIME

Serious damages caused by recent floods (e.g. New Orleans in USA, Marseille and Nîmes in France) have shown how important it is for the municipalities and transport infrastructure operators to have efficient and adapted reactions. Faced with a flood crisis, decisions have to be taken based on the current information available that is often very limited due to the lack of time to obtain, manage and analyse it. In Nîmes, a Mediterranean city exposed to very intense precipitations (more than 400mm in 6 hours), the 1988 flood resulted in 600 million Euros of damages, 10 deaths and 45,000 disaster victims.

In this context, the Nîmes City Council has conducted the elaboration of a new tool able to forecast and manage urban flooding in real-time [10]. ESPADA (Evaluation and Track of Rainstorms in Agglomeration to Anticipate Alarm) aims to anticipate the crises, by hydro-meteorological monitoring and provision of an organization with adapted means (see Figure 9).

Figure 9 – The ESPADA system

The ESPADA system is able to perform the following tasks in real-time:

- Early meteorological forecast through a modelling system based on predicted precipitations from radar imagery (every 15 min. for each sub-basin of the catchment area), allowing extreme rain events to be anticipated with pertinent accuracy;

- Early hydrological forecast, based on a rainfall-runoff model, and a hydraulic model developed for urban areas (supplied with 10 rain gauges, 20 water level recorders, with data collected every 10 min.);

- Early warning of flood risks by a risk analysis model representing flood intensity and providing immediate correlation of the on-going meteorological and hydrological situation to flood scenarios pre-defined from the previous extreme flood events (see Figure 10;

- Management and adjustment of flood scenarios and alerts allowing crisis plan implementation to be adapted and sped-up.

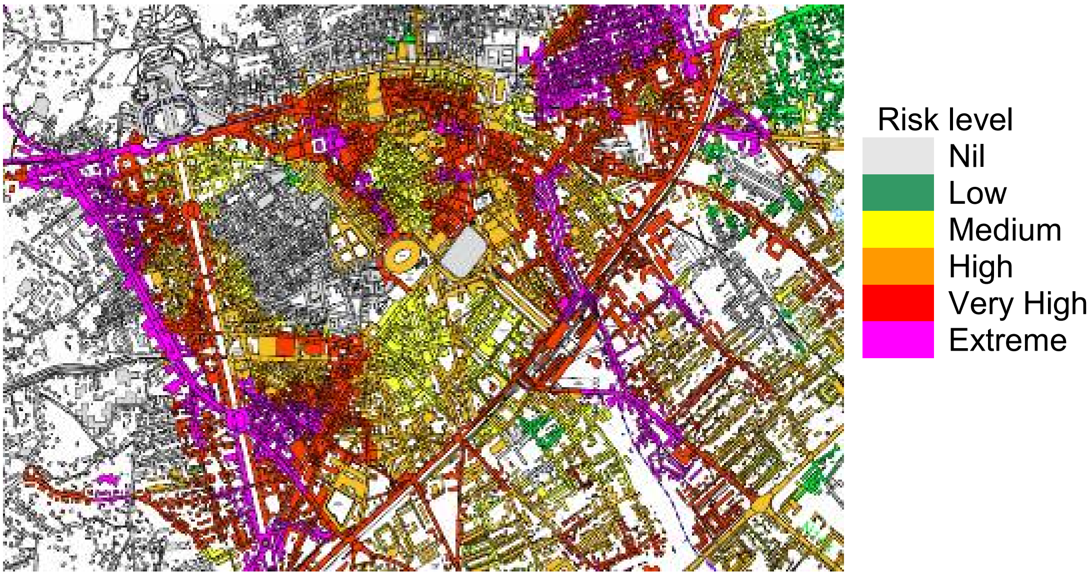

Figure 10 - Example of flood scenario (hazards + vulnerabilities) used with the ESPADA system for the Nîmes city

This ready-to-use system includes the complete equipment required for the crisis control room (furniture, data-processing equipment, software, communication equipment, automatic calling system, secured power, guarantee and maintenance) as well as in-situ video control.

Figure 11 - The Nîmes city flood crisis room

First results in the field, obtained for the floods that occurred in September 2005 (estimated to have a 50 year frequency), were deemed very satisfactory. The ESPADA system is therefore very promising and is evidence of the significant advancement obtained when combining growing computer power and increasing urban hydrological knowledge.

ESPADA was awarded the Special National Prize for Engineering from the Ministry of Public Works and Infrastructure in 2006, and is now used in more than 18 locations/cities.

7. ALERTING INFRASTRUCTURE OWNERS, OPERATORS AND USERS

The catchment area of the Lez (a river with a very changing regime) stretches over 455 km² and 28 districts (in the French "Départements" of Drôme and Vaucluse). The damage caused by the latest floods (1993 and 2003) showed the importance of the challenge in both human (3 dead persons) and financial (€ 520 M) terms. The Lez is managed by the Lez Catchment Area Joint Authority (SMBVL) which decided to acquire a complete and operational system able to quickly and reliably alert the population in case of flood risk but also during low water periods.

The resulting TRACE (Radio Telecommunication System for Flood and Low Water Alert) project led to a unique and innovative patented tool showing the following functions [11]:

- Transmission of information on the hydro-meteorological conditions of the catchment area with data provision in real time through the internet;
- Real time transmission of flood or low water alert on the basis of pre-defined thresholds;
- Securing information transmission during exceptional meteorological events (disruption of classic transmission methods and saturation of networks) with the setting-up of an owner's digital radio network for SMBVL (see Figure 12);
- Transmission of the information and receipt of alerts on pagers (digital radio method) to the members of the crisis units in the 28 town councils involved.
- Setting up an outsourced mass call system to alert the population in the catchment area exposed to the risks;
- Putting satellite telephones at the town councils' disposal for communicating with the outside when managing the crisis and during post-crisis periods.

Thanks to its principle based on the definition of customized alert thresholds (floods, low waters), the system is sustainable and makes it possible to adapt to changes in catchment areas (urbanisation, works in rivers, etc.) and climate changes. This turn-key alert system is of course adaptable to the needs and requirements of transport infrastructure owners, operators and users.

Figure 12 – Automatic gauging station with telemetry system incorporated, installed within the TRACE project.

8. CONCLUSION

In the face of climate change and contrary to generally accepted ideas: 1) there is no time to lose; 2) it is possible to act usefully as from today. Three types of approach are essential:

- Certain design principles, especially those which are used for sizing hydraulic structures should be modified. Based on the use of statistical series under a supposedly unchanged climate, they prove to be obsolete – or even dangerous – with a rapidly changing climate (cf the El Niño case study in Peru). These normative approaches look likely to be progressively replaced by methods based on risk analyses (cf the RIMAROCC approach), already implemented in association with cost-benefit analyses on sites showing a major challenge in terms of protection against natural risks. It should be pointed out that the extra cost generated by such adaptation is generally limited when the action is decided on as from the design stage.

- The design and operation processes should be adjusted. They should give rise to wider cooperation: with the weather services, between designers and operators (fair equilibrium between the "hardening" of the infrastructure facility and the adjustment of the maintenance and operation conditions), between transport modes (in order to guarantee the continuity of services to users), with the local stakeholders (to integrate the socioeconomic stakes). The notion of "reduced but acceptable level of service" should develop in concrete terms, in order to better optimise the operation of the infrastructure during crises which may become more frequent and less foreseeable. It is through overall and transverse brainstorming conducted at institutional level that concrete and cost-effective solutions can be found (cf case study in Morocco).

- The existing infrastructure facilities require concrete actions to be implemented. The analysis of the general criticality of each network section (reference situation) is an essential stage, depending on alternative routes, evacuation requirements, the densely populated/employment/hospital areas which are served, etc. It enables the "domino effects" to be assessed and the strategic infrastructure to be identified and dealt with on a priority basis. Then, the Owners have to start assessing and treating the risks resulting from the climate change. Relevant methodological tools and approaches (RIMAROCC, GERICI, ESPADA, TRACE, etc.) are already available or being developed.

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