Flood risk: a new approach for roads vulnerability assessment

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Abstract: A new approach to assess roads vulnerability in flood events is here presented. The main results of a case study, the road networks in Tiber floodplain, are also discussed. The new analytical model is based on Multi-Criteria Analysis (MCA) that assigns a vulnerability value to each road element (embankments, viaducts,..) depending on its structural and functional characteristics. Thanks to the specific framework of the model, also vulnerability causes can be easily determined enabling decisions makers to create meaningful future scenarios and to explore different strategies for an efficient vulnerability, and so risk, mitigation. Showing the effects of strategic alternatives in the long-term, this model allows a new wider and sustainable approach in flood risk management. Here the new approach has been used to assess roads vulnerability and risk, and then, to draw out vulnerability and risk maps. These maps are fundamental in emergency planning. The study also shows how the model could represents a useful decision support tool enabling decisions makers to determine evacuation possibilities and potential shelters, as shown in the Monterodondo case here presented. Using the maps, points of weakness in the area have been pointed out: these are especially viaducts crossing the river. On the other hand, using the model as a checking tool, different vulnerability mitigation measures have been planned and checked for critical elements, as shown in the example of the SP18a 'Via Traversa del Grillo' viaduct.

Key-Words: Vulnerability, Flood, Risk Assessment, Risk Management, Sustainability, Tiber

1 Introduction

A sustainable approach in road design and management requires a wider vision and it must include not just road structure and road users but also environmental impact on three targets, humans, environment and resources, and the ability of roads to face natural hazards. Natural hazard and environmental impact are closely related: the effect of a bridge crossing a river on overflows is the more severe the greater is the interference of structural elements of the bridge with the river regime. Moreover, during flood events collapsed bridges increase negative effects of overflows. On the other hand where natural hazards exist environmental impacts increase if a risk management is not planned. In recent decades, due to expansive and intensified land use, damage potentials in floodplain areas raise and, thus, conflicts between road infrastructures and flood risk increase. So in floodplain areas road safety implies flood risk management. Planning strategies focused on the sustainable development adopt ecological approach and both regional and urban planning are founded on ecological bases (Celikyay, Cengiz, 2006 [1]).

Sustainable flood risk management requires policy making for long term: *'decisions taken today will have a profound impact on the size of flood risks that future generations will need to manage. They will also strongly influence the options available for managing those risks'* (Evans et al., 2004 [2]). That means dealing with many uncertainties and many possible future and also examining different policy alternatives. This implies the creation of meaningful future storylines, in that plausible drivers of change (future scenarios) and potential management response to these (strategic alternatives) are reflected, as stated in recent FLOODsite reports (Klijn et al., 2009 [3] and Mc Gahey et al., 2009 [4]).

Attempting to determine which will be the size of flood risk in future scenarios and what will be the impact of strategic alternatives on these, it is fundamental to assess road vulnerability when it is facing flood risk. Target vulnerability in risk assessment represents its potential to be harmed by hazardous events. An element at risk of being harmed is the more vulnerable the more it is susceptible to hazard forces and impacts.

Moreover, most of strategic alternatives are focused on vulnerability reducing. So new questions are needed to be answered: what happens in terms of vulnerability when condition changes (future scenarios)? what happens if a set of vulnerability mitigation measures (strategic alternatives) is carried out?

2 Scope of the research

Scope of the research is to provide an analytical model for the assessment of current and future road vulnerability in flood events. The model should integrate multiple and complex relationships between natural hazard, road vulnerability and the impact of measures and instruments for risk mitigation. In the past few years many studies focused on flood simulation (Ghazali and Kamsin [5], Zaho et al. [6]) have been carried out but just few have considered the effects of overflows on road infrastructures. Some of them are about bridges vulnerability and damages caused by floods and they investigate mutual interferences between bridges and fluvial dynamics (e.g. Turitto et al., 2008 [7,8]). They are focused on just one structural element, the bridges, and they cannot be used to verify the whole network. However, the model should have the ability to adapt to every different element of the road, viaducts, embankments, cuts, grades and others (*adaptability*), considering all the mechanisms that contribute separately or in combination to the element breakdown (*sensitivity*). The model also should perform well in all contexts given (*robustness*). It should give an objective vulnerability assessment (*objectivity*) and it should be *easy to use*.

3 A new analytical model for road vulnerability assessment

A novel approach based on Multi-Criteria Analysis (MCA) is here proposed to handle the complexity of breakdown causes and dynamics. Flood Simulation

For each road element j vulnerability V_j is determined by (1):

$$V_j = \sum_{i=1}^{N} \gamma_i \cdot p_i \qquad (1)$$

where p_is are vulnerability parameters and γ_is quantify the effect of each parameter on total vulnerability (they represents degrees of freedom in this model) . p_is are hydraulic, geotechnical, structural and functional parameters (*sensitivity*). This type of information can be gathered from on-the-spot investigations or, for characteristic that may change (for example, the position of piers and abutments in the channel or the position of the bridge approaches in the floodplain), using remote sensing data, such as satellite imageries and aerial photos (Kumar, Singh [9]).

A specific parameters set is defined for each typological element (*adaptability*), so we have four different sets (see charts in Fig. 4, 5, 6, 7).

Each parameter can assume three different values 0, 1 and 2 whether they imply low/none, medium or high vulnerability for the element. Quantitative and qualitative vulnerability parameters have been defined. Assignment of values is based on the values assumed by the entity considered for quantitative parameters, on qualitative assessment categories for qualitative parameters. Next examples could clarify how to assign a specific value to parameters. Parameter *Contraction Factor* is a quantitative parameter: three ranges are defined, one for each value that the parameter can assume. It belongs to the viaducts parameters set and it represents contraction of flow due to the bridge that increases local scour around viaduct foundations (local scour is one of the main causes of bridge failure). It is 0 when the decrease in flow area results less than 25%, 1when it is from 25% to 50% and 2 when it is more than 50% (see chart in Fig.1). In chart in Fig. 2 the correspondence between qualitative categories defined for *Placement and type of vegetation* parameter and 0,1 and 2 values is presented. This parameter belongs either to Embankments and Cuts parameters set. Vegetation (herbaceous, shrub and tree) affects the stability of sloping land and it can initiate mechanical and hydrological processes resulting in an increase, or decrease in some cases, in shear strength.

This approach, based on just three different values 0, 1 and 2 for each parameter, makes the values assignment easier and it avoids the uncertainties of more detailed assessment metrics (*easy to use*).

α < 0,25	0
0,25 ≤ α < 0,50	1
α ≥ 0,50	2

Fig. 1: Values for *Contraction Factor* parameter

The vegetation determines mechanical **and** hydrological processes helping the stability of the slopes	0
The vegetation determines mechanical **or** hydrological processes helping the stability of the slopes	1
No vegetation / The vegetation does not determine mechanical or hydrological processes significant for the stability of the slopes	2

Fig. 2: Values for *Placement and type of vegetation* parameter

Generally, the main limit of MCA approach is that it can be subjective in its application because who applies the method decides on his/her experience how to fix any degree of freedom of the model (γ_i in the equation above). The novelty of the proposed approach is in this calibration phase: γ_is are determined using real data under a linear optimization process (*objectivity*). More in depth all γ_is used in the model for integrating different evaluation criteria (about 50 criteria) are estimated from the reports of the Civil Protection Agency that list the damages of road networks after floods in different Italian areas. For each element considered, an equation has been obtained (2):

$$V_j = \gamma_1 \cdot p_1 + \gamma_2 \cdot p_2 + .. + \gamma_n \cdot p_n \qquad (2)$$

Overall about 100 different cases[1] have been studied, getting an equation system (3):

$$\begin{cases} \gamma_1^1 p_1^{1*} + \gamma_2^1 p_2^{1*} + \gamma_3^1 p_3^{1*} + \ldots + \gamma_N^1 p_N^{1*} = V^{1*} \\ \gamma_1^2 p_1^{2*} + \gamma_2^2 p_2^{2*} + \gamma_3^2 p_3^{2*} + \ldots + \gamma_N^2 p_N^{2*} = V^{2*} \\ \ldots \\ \ldots \\ \gamma_1^M p_1^{M*} + \gamma_2^M p_2^{M*} + \gamma_3^M p_3^{M*} + \ldots + \gamma_N^M p_N^{M*} = V^{M*} \end{cases} \qquad (3)$$

By the optimization process based on mean square error (MSE) method the γ_is set that guarantees the larger overlapping of real vulnerabilities V_j* and model vulnerabilities V_j has been obtained (see the graph in Fig. 3).

The models obtained for the four typological elements are shown in the charts in Fig. 4, 5, 6, 7.

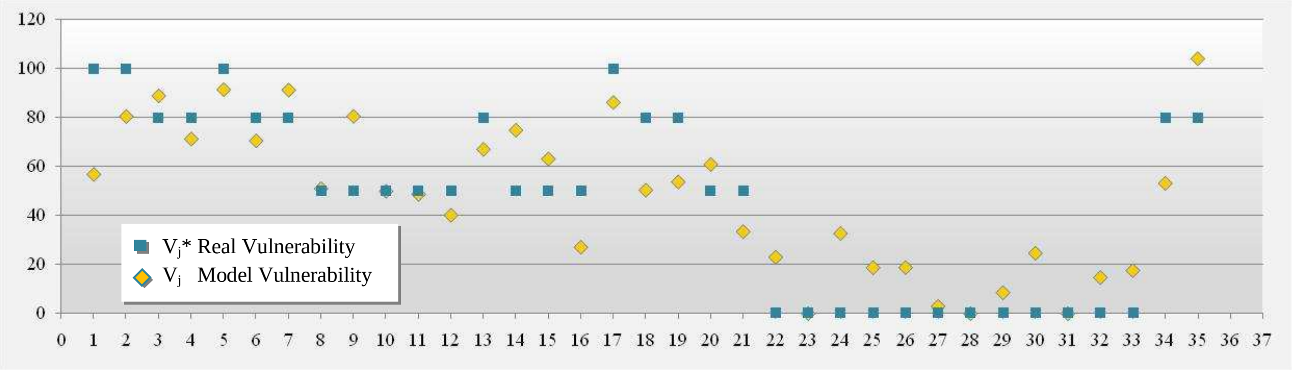

Fig. 3: Real vulnerability V_j* and Model vulnerability V_j for *n* viaducts

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[1] Reports of the Civil Protection Agency used in the calibration are about road infrastructures in basins of 8 different rivers in Northern Italy. Despite the differences between Northern Italy rivers and the Tiber (the case study) good results have been obtained in the case study, showing the *robustness* of the model presented.

PARAMETERS		***WEIGHTS***	
V1	contraction factor α	γ_{V1}	***5,597***
V3	angle of attack of the flow	γ_{V3}	***4,902***
V6	amount of bed material in transport	γ_{V6}	***28,322***
V8	position of piers and abutments in the channel	γ_{V8}	***19,479***
V9	position of approaches in floodplain	γ_{V9}	***12,048***
V10	amount of approaches material in transport	γ_{V10}	***10,975***
V11	orientation of the bridge	γ_{V11}	***1,896***
V13	portion of the viaduct exposed to the flood of design RI	γ_{V13}	***9,911***
V15	safety of approach embankments F_r	γ_{V15}	***15,952***

Fig. 4: Viaduct model (viaduct with no protective materials are considered)

PARAMETERS		***WEIGHTS***	
R1	water inside the embankment	γ_{R1}	***18,390***
R2	embankment slope	γ_{R2}	***15,164***
R3	placement/loss of protective materials	γ_{R3}	***11,681***
R4	placement and type of vegetation	γ_{R4}	***2,656***
R5	amount of embankments material in transport (erosion risk)	γ_{R5}	***28,049***
R8	transverse roadway slope i_t	γ_{R8}	***12,427***
R10	pavement condition	γ_{R10}	***1,721***

Fig. 5: Embankments model

PARAMETERS		***WEIGHTS***	
T2	mechanical resistance of slopes	γ_{T2}	***1,362***
T3	placement and type of vegetation	γ_{T3}	***0,615***
T4	landslide risk	γ_{T4}	***42,618***
T5	longitudinal roadway slope i_l	γ_{T5}	***1,302***
T6	transverse roadway slope i_t	γ_{T6}	***31,983***
T7	placement and type of conduit system	γ_{T7}	***6,920***

Fig. 6: Cuts model

PARAMETERS		***WEIGHTS***	
A1	longitudinal roadway slope i_l	γ_{A1}	***0,861***
A2	transverse roadway slope i_t	γ_{A2}	***11,761***
A4	pavement condition	γ_{A4}	***2,838***
A5	landslide risk	γ_{A5}	***14,659***
A6	amount of material in transport (erosion risk)	γ_{A6}	***33,152***

Fig. 7: Grade level model

4 A case study

The road network of Northern Rome in Tiber floodplain represents the case study on which the model has been formerly used. The main results of this study are here discussed.

This floodplain is crucial for the safety of the city of Rome during flood events. In fact, it can storage about 190 millions m^3 of water preventing the river from flooding in several points within the city. The sections of two important motorway (green colored in Fig. 8) cross the floodplain, A1, that connect Naples and Milan, and A1 Dir that represents the link of the A1 to the Rome urban road network. These are accompanied by regional links (blue colored in Fig. 8): S.S.n.4 Via Salaria and S.P. n.15a Via Tiberina that run along the river and are connected by S.P. n.18a Via Traversa del Grillo (the only local road crossing the river in this area); S.S.4Dir and S.S. n.3 Via Flaminia; finally, local roads that connect towns and regional roads.

Using the new approach to evaluate vulnerability of this case study the flood risk assessment has been easier to carry out and the whole disaster management cycle, from risk reduction to readiness, response and recovery could be facilitated (Iyer, Mastorakis [10]).

Road Vulnerability Map in Fig. 9 and Road Risk Map in Fig. 10 show two of the main steps in the risk assessment process and represent two useful decisions support tools. Road Risk Map helps road management in emergency phases, during and after flood events, enabling decisions makers to determine evacuation possibilities and potential shelters. On the other hand, Road Vulnerability Map shows weak points in road network pointing out which direction risk mitigation strategies should take. Short and mid term strategies defined for this case study are here briefly presented.

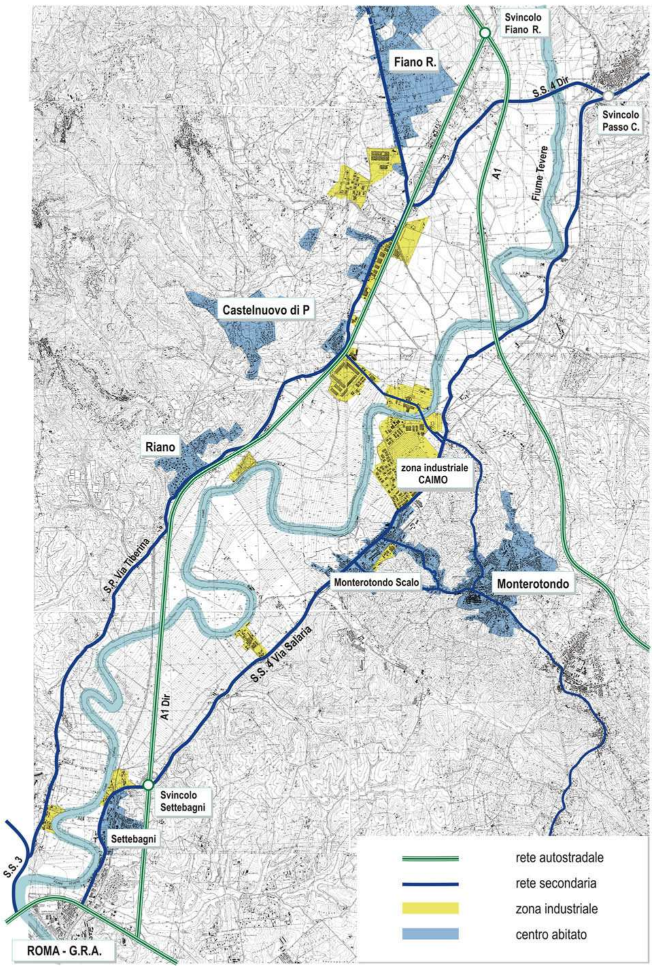

Fig. 8: Road network in the area

In the short term the evacuation plan for the area and the check of the functionality of the road network after the overflow have been carried out. Emergency plan is the cornerstone of preparedness, which should cover the readiness, response and recovery, and guaranteeing communications is one of the most important

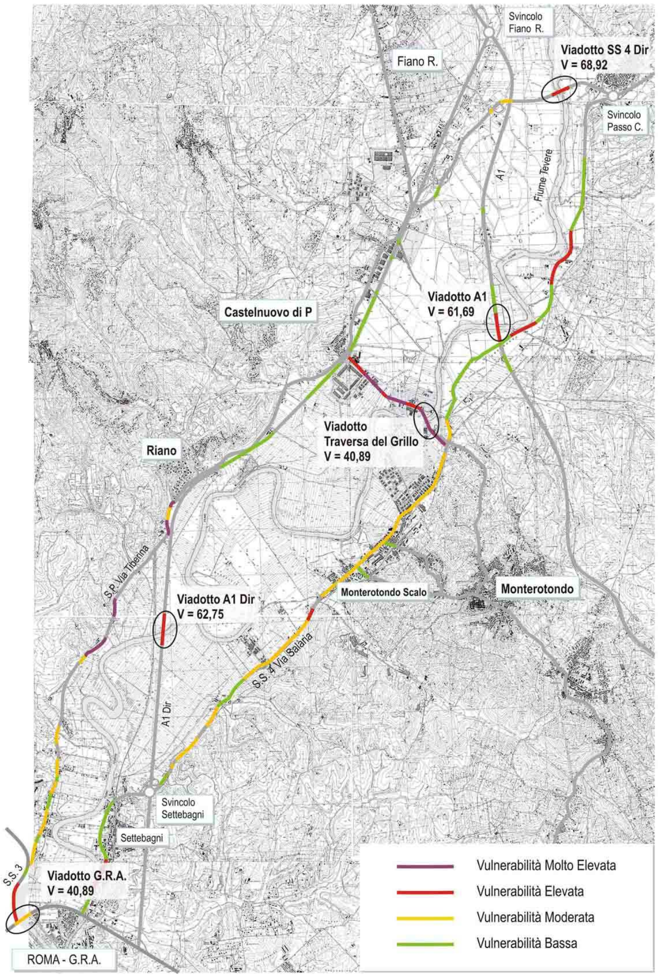

Fig. 9: Road Vulnerability Map

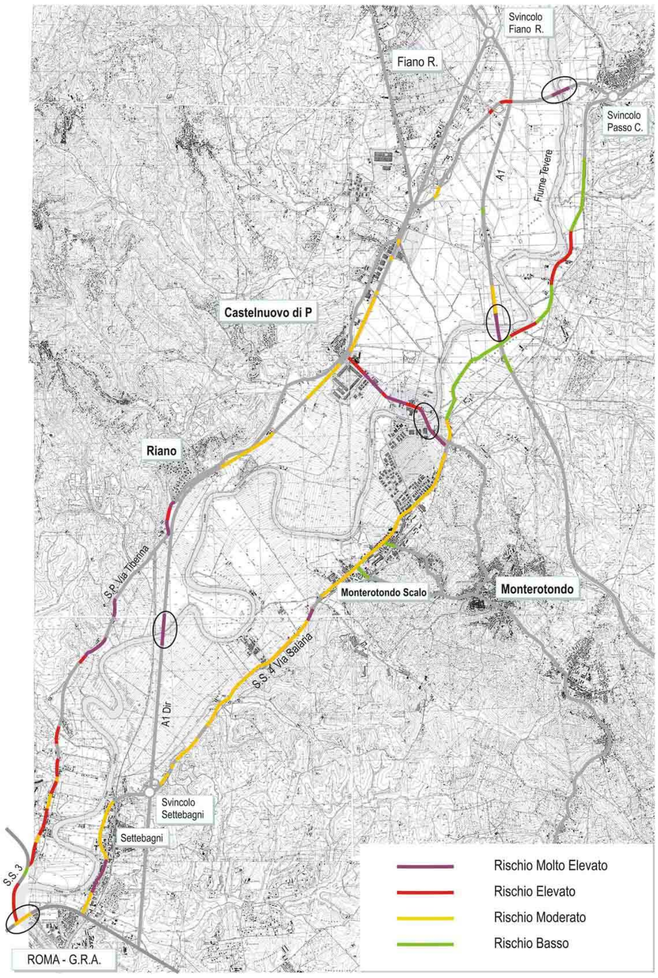

Fig. 10: Road Risk Map

requirements [10]. The evacuation plan studied for residential (38760 inhabitants) and industrial (6000 workers) areas in Monterotondo is one good example of the usefulness of the model in short term strategies planning. The plan has been arranged, assuming as a baseline scenario the 200 years period flood event. Levels of the risk on road network determined by the model shows that areas at risk, particularly that ones on the left side of the S.S. n. 4, are going to be isolated after the overflow (Fig. 12). That induces to concentrate the evacuation activity before the event. For the 200 years period flood event the average speed of propagation of the flood in riverbed is 1.9 m/s and the propagation time between two consecutive hydrometers are shown in Fig. 11. When the flood reaches Ponte del Grillo hydrometer (it is located by the SP 18a 'Via Traversa del Grillo' bridge), there is the overflow in the area. The Ponte Felice hydrometer could be taken as the reference: it is upstream the section of the case study and, according to the propagation times, the flood would take 8 hours and half to reach the area from this hydrometer. Within the 8 hours and half ordinary routes can be used to evacuate and reach the recovery areas.

Hydrometers	Propagation time
Orte Scalo – Ponte Felice	2 h and 30 mins
Ponte Felice – Stimigliano	2 h and 20 mins
Stimigliano – Nazzano	4 h and 40 mins
Orte Scalo – Ponte del Grillo	11 h
Ponte Felice – Ponte del Grillo	**8 h and 30 mins**
Stimigliano – Ponte del Grillo	6 h and 10 mins
Nazzano – Ponte del Grillo	1 h and 30 mins

Fig. 11: Propagation times of the flood

In the mid term mitigation risk strategies are focused on decreasing vulnerability of roads. In this case study area crossing the river during and after a flood event represents the main problem.
There are five bridge crossing the Tiber, two of them are part of highways and three belongs to the rural roads network.

One of them (Fig. 13) is here discussed to clarify how the model can be efficiently used not just in vulnerability and risk assessment but also to verify different strategic alternatives. This viaduct belongs to the rural road SP 18a 'Via Traversa del Grillo' and its construction standards are very poor. The model has been applied to five scenarios: the current scenario and four future scenarios. For future Scenario 0 it is assumed that no mitigation measures are carried out and so some current phenomena, like bed scour, gets worse. The other three future scenario have been drawn considering the vulnerability causes that the application of the model to the current condition had shown (they are summarized in the chart in Fig. 14). In these it is respectively assumed that mitigation measures on flow direction are carried out (Scenario 1), mitigation measures reducing bed scour and approaches erosion are carried out (Scenario 2), mitigation measures reducing section contraction due to the bridge are carried out (Scenario 3).

In the chart in Fig 15 scenarios are summarized and variations on vulnerability rate are shown for each strategic alternative.

The application of the model has shown that the strategic alternative in scenario 2 is the most efficient, pointing out that bed scour and approaches erosion is the most critical cause of vulnerability for this case study. In fact, the alternative in Scenario 2 reduces vulnerability rate for SP18a viaduct from 62,0 to 17,5 (- 71,8%).

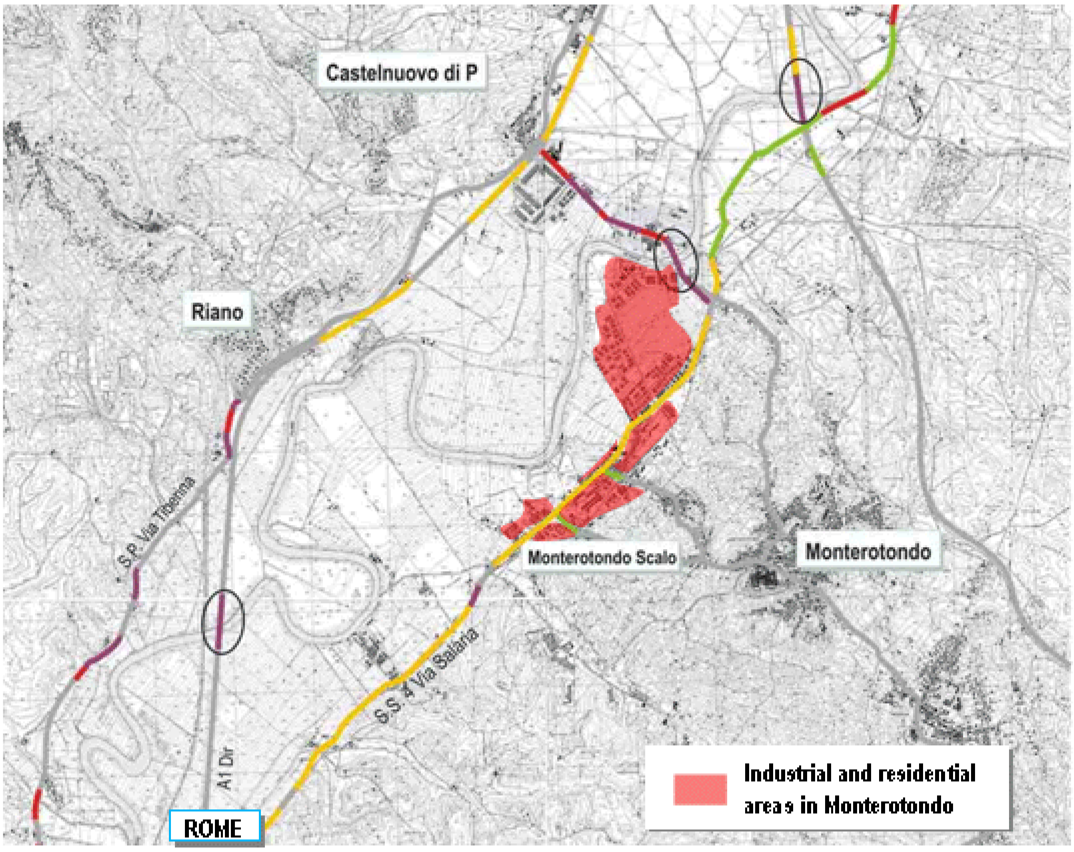

Fig. 12: Risk for road network in Monterotondo area

Fig. 13: SP18a viaduct

Vulnerability Causes		***V***
▪ **section cross contraction**	contraction factor (r = 47,8) V_1	***62,04***
▪ **orientation of piers**	angle of attack (β = 15°) V_3	
▪ **bed scour and approaches erosion**	amount of bed material in transport V_6	
	amount of approaches material in transport V_{10}	
▪ **piers and abutments into the channel**	piers in bed and abutments projecting into the channel V_8	
▪ **position of approaches in the floodplain**	bridge approaches cutting off the floodplain flow V_9	
▪ **natural alignment of the channel**	bridge at a channel bend V_{11}	

Fig. 14: Vulnerability causes for SP18a viaduct

Scenarios			*Effects*	
N.	***Measures***	***Vulnerability Parameters affected***	***V***	***ΔV [%]***
C	-	-	***62,0***	-
0	-	-	***80,3***	***+ 29,4***
1	On **flow direction**: 1) guide banks, dikes, and spurs (usually constructed of earth and rock) *or* bridge wingwalls 2) flow deflectors or semicircular/ triangular endnoses	V_3 angle of attack of the flow V_6 amount of bed material in transport V_9 position of approaches in floodplain V_{10} amount of approaches material in transport (V_{11} orientation of the bridge)	***48,9***	***-21,2***
2	Reducing **bed scour and approaches erosion**: 1) concrete or wire and rock mattresses on bed *or* pier on shaft foundations 2) approach embankment protections, such as riprap *or* timber bulkheads	V_6 amount of bed material in transport V_9 position of approaches in floodplain V_{10} amount of approaches material in transport	***17,5***	***-71,8***
3	Reducing **section contraction**: 1) Additional bridge openings or spans	V_1 contraction factor α V_6 amount of bed material in transport V_9 position of approaches in floodplain V_{10} amount of approaches material in transport	***42,5***	***-31,5***

Fig. 15: Current condition and strategic alternatives effects

5 Conclusions

The model here discussed represents a complete and useful alternative way to assess road vulnerability. It quantifies vulnerability assigning a specific value to each road element based on all the factors (*vulnerability parameters*) that contribute separately or in combination to the element breakdown.

It overtakes the main limit of MCA approach, the subjectivity, fixing any degree of freedom using real data. The robustness of the model depends on the amount of real data available for its calibration. In Italy, data on roads characteristics and any possible flood damages on them are available just in few cases, so how to extend this data base is still a remaining gap.

The model framework makes easy and immediate pointing out the vulnerability causes and quantifying *ex ante* the benefits of different flood protection strategies. Studying the effects of continuing the current strategy and the effects of strategic alternatives in the long-term allows to develop a wider vision on flood risk management, so it better motivates short and medium-term decisions and may help to prevent future regret.

Another point of strength of the model is that it is very easy to be implemented once the characteristics of infrastructures are known. This important property makes the model very useful also in emergency phases or in the preliminary and early stages of land use planning, as the Monterodondo area example demonstrates.

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