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► **To cite this version:**

R.P. Yordanova, C. Curt. Towards a systematic qualitative methodology for multi-hazards risk representation and preliminary assessment. 10èmes journées Fiabilité des Matériaux et des Structures, Mar 2018, Bordeaux, France. hal-01826285

HAL Id: hal-01826285

<https://hal.science/hal-01826285>

Submitted on 29 Jun 2018

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Towards a systematic qualitative methodology for multi-hazards risk representation and preliminary assessment

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RÉSUMÉ.

Ce travail vise à évaluer qualitativement les risques résultant de divers enchaînements directs ou indirects d'aléas naturels et technologiques pour la commune de la Ciotat. Une méthodologie qualitative systématique est proposée, basée sur une structure d'interaction cause-effet. Par ailleurs sont assignés : des conditions aux causes, des impacts aux effets, des barrières de protection et des types d'interactions à un flux donné entre une cause et un effet. Cinq classes d'interactions sont utilisées : déclenchements directs, déclenchements indirects, augmentation soit de la fréquence /de la probabilité d'occurrence, soit de l'intensité, soit de la vulnérabilité des éléments exposés. Les liens entre aléas sont conceptualisés et représentés via une matrice bidimensionnelle (« matrice d'interactions »). Plusieurs chaînes multirisques sont produites et notamment les différents scénarios les plus défavorables. La méthode est illustrée par le scénario d'incendie de forêt et les chaînes d'aléas possibles en résultant. Cette méthodologie d'appui, actuellement qualitative, est une première étape vers un outil pour la gestion multirisques.

ABSTRACT.

This work aims at qualitatively assessing risks resulting from various direct or indirect chains of natural and technological hazards for a defined geographical/administrative area - the community of Ciotat. A systematic qualitative methodology is proposed based on a cause-effect interaction structure that assigns conditions to causes, impacts to effects, protection barriers and types of interactions to a given flux between one cause and one effect. Five classes of interactions are used: direct triggers, indirect triggers, increases in frequency/probability of occurrence, in intensity and in the vulnerability of the exposed elements-at-risk. Various hazards links are conceptualized and represented via a two-dimensional matrix abbreviated as matrix-of-interactions. It contains every possible interaction, therefore chains of multi-hazards are produced that approximate different worst-case scenarios given a set of initial causative conditions. A scenario of wildfire and its hazard chain is demonstrated in detail. In its qualitative form, this supporting methodology proves useful tool for the decision-making processes of multi-hazards risk assessment and management.

MOTS-CLÉS: multi-*risques, scénarios d'évaluation des risques, enchaînements d'aléas*

KEYWORDS: multi-hazards risk, risk assessment scenarios, hazard chains

Introduction

Human settlements are often situated in zones such as the floodplains of rivers because they offer large availability of arid lands, or near the sea to exploit the advantages of large water bodies for fishing, trade etc. However, often these regions are threatened by a combination of hazards occurring due to mutual interrelations either quasi simultaneously (flood and ground destabilisation such as mudslide) or in a sequence (earthquake and aftershocks) or simply coinciding (earthquake and storm) (Gill and Malamud, 2014; Kappes et al., 2012). In every situation the overall risk produced due to these combinations can be greater than the mere addition of the individual risk of each event. Therefore, the importance of addressing the totality of the possible hazards that may take place in a single incident is becoming more and more recognized. As a result, the term multi-hazards now appears in important international policies aiming at risk reduction such as the Agenda 21 (UN, 1993), the Hyogo Frame for Action, in IPCC reports (IPCC, 2012) and more. There are many defined challenges in multi-hazards risk

assessment approaches firstly related to the lack of generally applicable terminology and conceptual baseline (Kappes et al., 2012). However there is a growing awareness that risk is a combination of three factors, namely hazard, exposure and vulnerability (UNISDR, 2009). In this work we define multi-hazard risk as a set of different hazards (of natural or technological origin) that spatially and/or temporally coincide and act in a combined way, such that they trigger secondary events and/or cause increased frequency and probability of occurrence of secondary hazards and/or increase the vulnerability of the exposed elements-at-risk.

A synthetic holistic consideration of all possible and spatially relevant natural hazards has only recently raised interest and thus few authors have made considerable contribution to the field (Greiving, 2006; Kappes et al., 2012; Marzocchi et al., 2012; Nadim et al., 2013). In addition, the consideration of anthropogenic processes and technological hazards that influence negatively the manifestation of natural risk is almost non-existent with very few exceptions (Gill and Malamud, 2017, 2016). The purpose of this work is to study these emerging ideas and derive a synthetic and systematic approach for qualitatively assessing multi-hazards risk in a given area of study.

This work is organized as follows: the challenges of assessing multi-hazards risk as well as the existing methodologies are discussed in the form of a state-of-the-art literature analysis. Next the global approach for producing multi-hazard risk scenarios for their assessment is decomposed and its steps are followed throughout the paper. Therefore, the area of study is briefly presented in a manner that stresses the types of hazards that have historically impacted the area (i.e. problems that actually exist and have not been addressed under the context of multi-hazards risk). Next, the method for including multiple types of interactions and scenario production is shown and applied with reference to the key study. The analysis results in a preliminary assessment of the aggregated risk of wildfires which is discussed in the final section of this paper, along with some future work perspectives. Lastly, a conclusion is added.

Addressing the challenges for multi-hazards risk assessment in existing approaches

A) Existing risk assessment approaches: Different risk assessment techniques have been summarised by ISO (International Organization for Standardization, 2009, pp. 22–26) some of which can have an application on multi-hazards risk analyses. Generally, different authors use different techniques depending on their level of expertise, the type of input data they dispose and the desired output of analysis (qualitative or semi-/quantitative). Three main types of approaches can be pinpointed. Firstly, risk quantification with (sometimes weighted) indicators and indices, e.g. (Greiving, 2006; Schmidt-Thomé et al., 2010), which is probably the only method for quantifying vulnerability given that it's subjective and dynamic ergo unquantifiable. Secondly, matrices of type frequency/intensity that are used to form a "risk matrix" and rank impacts, e.g. (Komendantova et al., 2014; Schmidt-Thomé et al., 2010) or matrices that integrate two hazards in some interactive form, e.g. (De Pippo et al., 2008; Gill and Malamud, 2017, 2014; Kappes et al., 2010; Tarvainen et al., 2006). Scenarios can be built from interactions provided in these matrices. Lastly, probabilistic approaches are used for quantitative assessment e.g. (Liu et al., 2016; Marzocchi et al., 2012, 2009), which in the multi-hazard risk context are used for limited types of hazards interactions mostly when one hazardous event directly triggers a secondary hazardous event. Our proposal is to use matrices and scenarios for a systematic representation of multi-hazard risk interactions.

B) Identifying challenges: The previously discussed approaches for estimating risk vary significantly and most often are designed for addressing efficiently one or two aspects of the risk equation. Therefore the main goal should be integrating the physical characteristics (hazards and exposure) and vulnerability components in a multi-hazard risk perspective. This is challenging for two main reasons; firstly the physical characteristics of natural and

anthropogenic hazards may differ significantly (with respect to their predictability and the location, scope, type and timescale of impact) and require their harmonization i.e. finding a method that will enable risk managers and decision makers to compare physical and anthropogenic processes of different nature, as a prerequisite to assess their mutual impact potential (Liu et al., 2015; Marzocchi et al., 2012). Secondly, integrated vulnerability assessment is quite difficult when there are multiple, dynamic processes acting in a joint manner and thus requires fine analysis, increased expertise and shared knowledge for efficiently assessing disaster risk (Komendantova et al., 2014).

Therefore the question is can we develop a systematic and comprehensive methodology that will allow addressing multi-type interactions? How can it include the concepts of vulnerability so that no aspects of risk are neglected? Can it be transferable from one community to another? The methodology that is used here to tackle these inquiries is presented in the following section.

Presentation of the global approach used for multi-hazards risk assessment

The approach for formulating the multi-hazards risk assessment methodology is presented in the following figure (Fig. 1) as a stepwise process of 5 consecutive steps: (1) identification of all the hazards (natural and classes of technological) for the given geographical/administrative area of study; (2) synthesis of all the cause-effect interactions, their main causative effects, resulting impacts and eventual protective barriers through a comprehensive versatile representation; (3) construction of a matrix of interactions (first binary then descriptive then typological); (4) production of scenarios for each hazard as a primary cause for chain initiation; (5) mapping hazards for preliminary assessment of risk resulting from the generated scenarios. This innovative approach is exemplified on the case of Ciotat in the following sections.

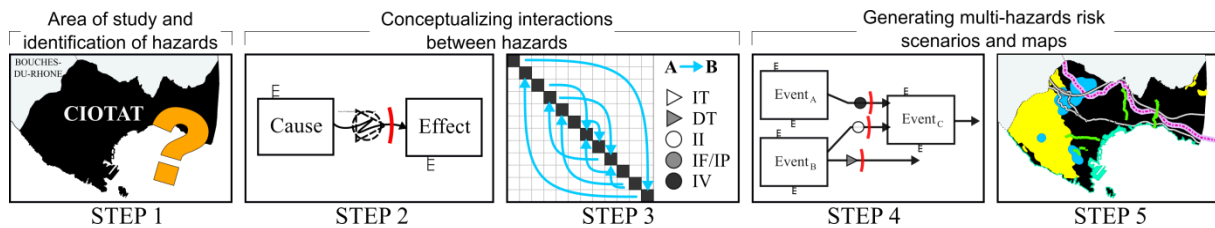


Fig. 1 : The global stepwise approach used for multi-hazards risk assessment

Area of study and identification of hazards

The selected area of study is the municipality (*commune*) of Ciotat, situated in a coastal region in the *Bouches-du-Rhône* department in the *Provence-Alpes-Côte d'Azur* region in southern France (Fig. 4). It is part of the metropolitan area of Aix Marseille Provence which generally is an area densely inhabited, especially around the coast. Its total area is 31.46 km², 47% of which is forest or natural land, its population is approximately 34000 citizens (according to Insee 2012) while it hosts around 85000 tourists per year. The area can be divided in 4 zones, the littoral zone, the central plain and two massifs, the “*Massif de Cap Canaille*” at the west which is quite arid and prone to fires and the “*Massif des Plaines Baronnes*” northeast of the old center. The climate is predominately Mediterranean humid and mild with an annual precipitation of around 525 mm and 80 rainy days. Winds generally dominate from the east while strong *Mistral* winds coming from the north, north-west are also frequent especially during the winter.

Step 1: Hazards identification

Many hazards of natural and technological origin menace the area of study – they are identified through historical data (events happened in the past can repeat in the future), studies of potential hazards (that have happened in nearby areas by not in Ciotat) and in situ estimation of elements-

at-risk (for estimating the technological risk). In particular, winds blowing in the littoral zone (mainly the Mistral) cause upwelling, which slowly erodes the (artificial) sandy beaches. The siliceous rocks in the area are also prone to erosion and rock fall, especially in some vertical segments along the coast. Coastal floods generated by storm surges have also occurred in the past. As far as its hydrology, there are three main streaks traversing the city that remain dry at some parts of the year. Underground tunnels allow seepage but their size and conditions of maintenance are insufficient for efficient drainage thus problems are likely to occur in extreme precipitation events, known to take place in southeastern France. In fact there have been three reported cases of waterspouts (tornados occurring over water) forming in the region, in the years 1983, 1995 and 2015. Forest fires also tend to occur on a yearly basis. In fact, in the massifs there is no direct access to water reservoirs and no water network; therefore, specially designed containers of water are placed throughout the forest for emergency cases. Finally, technological factors that seem of importance are the large industrial/commercial area which is situated close to the forest and four axes that run quasi-parallel to each other: the railroad, the highway marked as high risk zone for transportation of dangerous materials, the (underground) Gazoduk line, also marked as potential hazard due to the transportation of pressurized natural gas (Ville de la Ciotat, n.d.) and finally the high voltage power line (di Maiolo et al. 2015). All the natural and technological hazards identified for the area of study are summarized in the following table (Tab. 1).

Tab. 1 : Hazards classification and their possible (direct and indirect) interactions for Ciotat.

No	Group	Main hazard type	Abbreviation	Direct interactions	Indirect interactions
1	MET	Convective storm	CS	CF, HL, WD, RF, FF	TO, WF, MMW, IA, TA, MA
2	MET	Coastal flood	CF	MMW, MMD	TS, IA, TA, MA
3	MET	Hail	HL	-	MMW, IA, TA, MA
4	MET	Snow	SN	RF, FF, MMW	MMD, IA, TA, MA
5	MET	Tornado	TO	CF, WD	CS, MMD, IA, TA, MA
6	MET	Wind	WD	CS, CF, MMD	WF, IA, TA, MA
7	MET	Heat wave	HW	CS	DR, WF, IA, TA, MA
8	MET	Cold wave	CW	SN, WD,	HL, MMW, IA, TA, MA
9	CLIM	Drought	DR	-	HW, WF, MA
10	CLIM	Wildfire	WF	-	HW, DR, FF, MMW, MMD, IA, MA
11	HYD	River flood	RF	MMW	MMD, IA, TA, MA
12	HYD	Flash flood	FF	RF, MMW	IA, TA, MA
13	HYD/ GEO	Mass movement wet	MMW	TS, MMD	IA, TA, MA
14	HYD/ GEO	Tsunami	TS	CF, MMW	IA, TA, MA
15	GEO	Earthquake	EQ	MMW, TS, MMD	IA, TA, MA
16	GEO	Mass movement dry	MMD	-	FF, MMW, TS, IA, TA, MA
17	TECH	Industrial accident	IA	WF	MMD, TA, MA
18	TECH	Transport accident	TA	WF	MMD, MA
19	TECH	Miscellaneous accident	MA	WF, FF, MMW, TS	MMD, IA, TA

Possible interactions, either direct (prone to cause cascading hazards) or indirect (somehow affecting a secondary hazard) are extracted from numerous bibliographic sources, the press etc., and thus concrete information is added for assessing hazards' interaction in the area of study. The aim is to provide an all-inclusive table and to eliminate interactions that are not valid for the area of study during later steps of the process (part 4/5). As so, the methodology remains robust and transferable to similar geographic areas.

Conceptualizing hazards interactions

Step 2: Basic representation of cause-effect interactions

It is considered that is best to use a systematic and holistic approach able to conceptualize all the types of interactions between hazards, firstly in a basic interactive form easily transferable and from then on in chains that represent the multi-hazards risk based on the principle "all-hazards-at-a-place" (Kappes et al., 2012). One can start forming this representation using a basic cause-effect, source-target etc. representation such as the one proposed in the model MADS (Périlhon, 2007). Here we adopt the same principle of two elements connected with a flux that represents their interaction (Fig. 2). Conditions affecting the causative event and impacts of the resulting event are added. Based on the given working definition, we consider five possible interaction types: (1) direct trigger/cascade (2) delayed trigger/cascade (3) increased frequency/ probability of occurrence (4) increased intensity and (5) increased vulnerability. The temporal delay between cause and effect can be limited to the time necessary for the system to return to a normal state of function (response and recovery time). A significant addition is the protection barrier that refers to the possible structural or non-structural protective and mitigative measures that play an important role in risk reduction and should be an imperative part of risk assessment procedures.

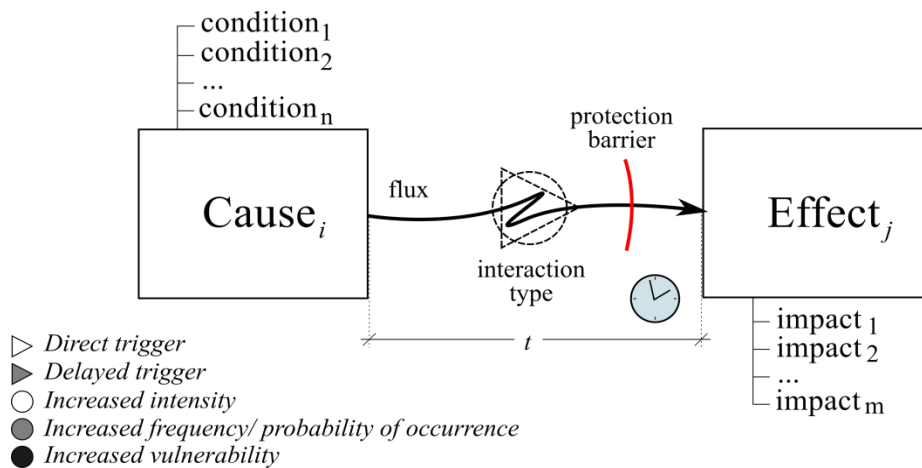


Fig. 2 : Basic representation of a cause-effect interaction diagram in coupled human-environment systems and introduction of the flux typology for this setting

The interaction starts due to a main causative event or hazard which takes place as a result of a number of initiating conditions (not direct part of the chain process). This provokes a secondary phenomenon that subsequently becomes the initiating condition for a tertiary effect and so on, thus creating a chain of events with multiple phases. The goal is to represent the worst-case scenario so that no aspects of risk, no matter how unlikely, are neglected.

Step 3: Matrix approach for systematic study of hazards' interaction

Probably the most efficient and easily transferable method of building chains of hazards' interactions is to use a matrix that summarizes all possible interactions between a causative event and a resulting event. For the example of Ciotat such matrix was formed by placing all the identified hazards diagonally, thus obtaining a 19x19 matrix. This configuration is read from row to column in a clockwise direction and in each intersection interactions are placed, firstly in a binary Yes/No form, then descriptive (expert judgement can elucidate the specific interactions) and then typologically categorized as one of the five classes of interaction (Fig. 3). If more than one type of flux applies, the most dominant is chosen in the representation for simplification and clarity. At later stages, according to the spatiotemporal characteristics of the phenomena and the scope of the analysis, interaction types can be modified. It is the decision-makers' judgement that defines the choice of interaction type and this choice is justified at the terrain.

	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	XIII	XIV	XV	XVI	XVII	XVIII	XIX
1	CS	IT	IT		II	IT				IV/IT	DT	DT	IV				IV	IF/IP	IV
2		CF											DT	II		DT	IV	IV	IV
3			HL										IV				IV	IV	IV
4				SN							DT	DT	DT			IV	IV	IF/IP	IF/IP
5	II	IT			TO	IT										IV	II	II	II
6	DT	IT				WD				II						DT	IV	IV	IF/IP
7	DT						HW		IV	IF/IP							IV	IV	IV
8			IF/IP	IT		IT		CW					IV				IV	II	II
9							IF/IP		DR	II									IV
10							IV		II	WF		II	II			IF/IP	IV	IV	IV
11											RF		IT			IV	IV	IF/IP	IV
12											IT	FF	IT				IV	IF/IP	IF/IP
13													MMW	IT			IT	IV	IV
14		IT											IT	IS			IV	II	II
15													IT	IT	EQ		IT	II	II
16												II	IV				MMD	IV	IV
17										IT						IV	IA	IV	IF/IP
18										IT						IV		TA	IF/IP
19										IT		IT	IT	IT		IV	IV	IV	MA

Fig. 3 : A possible matrix of hazard interactions with codes that aggregate the descriptive information to five categories of flux: IT – Immediate Trigger, DT – Delayed Trigger, II – Increased Intensity, IF/IP – Increased Frequency or Probability of occurrence, IV – Increased Vulnerability. Hazard codes are indicated in Tab. 1 and in the diagonal of the matrix

Every scenario starts with one main causative event, and then all the interactions, as derived from the table, are linked in a chain starting with the immediate triggers then adding delayed triggers and so on. An example of multi-hazards chain for the case of wildfires as derived from the interaction table of Ciotat is demonstrated in further detail.

Generating multi-hazards risk scenarios and maps

Step 4: Producing risk scenarios for the selected area of study

The scenario of wildfire (Hazard No10 in Tab. 1 and 10X in Fig. 3) is interesting for Ciotat because such events occur almost on a yearly basis. The hazard chain is constructed by using the information provided in the interaction table while examining each time if the given

information applies to the case and event study. Starting with wildfire there are eight possible secondary events that can be affected. On a vulnerability level (note: sometimes increased vulnerability equally refers to increased probability of occurrence but if it is not possible to quantify it, the interaction is conceptualized only in a vulnerability level and semi-quantitatively), wildfires occurring near urban areas that experience heat waves (10VII) further increase temperatures and make respiration difficult. Industrial, transport and other (miscellaneous) accidents (10XVII, 10XVIII, 10XIX) are also more prone given the specific conditions. Movement of mass in dry state such as rock fall, debris flow, erosion or other (10XVI) are more probable in the aftermath of a fire, given that the vegetation that buffers such effects is burnt. Wildfires increase the intensity of droughts (10IX) because of the loss of vegetation and water due to extreme heat. Finally they increase the intensity of flash floods (10XII) and mass movements in wet state (10XIII) due to the loss of vegetation and consequently infiltration capacity (larger quantity of runoff) and due to the excess of materials left after the fire (residual material from the combustion process) and carried in flashy waters. Possible tertiary hazardous phenomena are more wildfires occurring when related to droughts and/or heat waves, more intense river floods in the event of extreme flash floods and various technological hazards. The produced multi-hazard chain is seen in Fig. 4; events that are not relevant are excluded like for example the tsunami hazard that interacts with wet mass movement which appears in the interaction, yet so far, only underwater landslides are known to trigger tsunami hazards. As seen, it is possible to produce loops in the chain, usually on a vulnerability level but given that conditions are altered each time, the loops cannot be considered infinite in a given area. The importance of structural (e.g. levees to avoid the occurrence of MA/TA/IA due to RF) and non-structural measures of protection (e.g. warnings in DR-WF) is evident as they can significantly mitigate the resulting outcome of the progression chain.

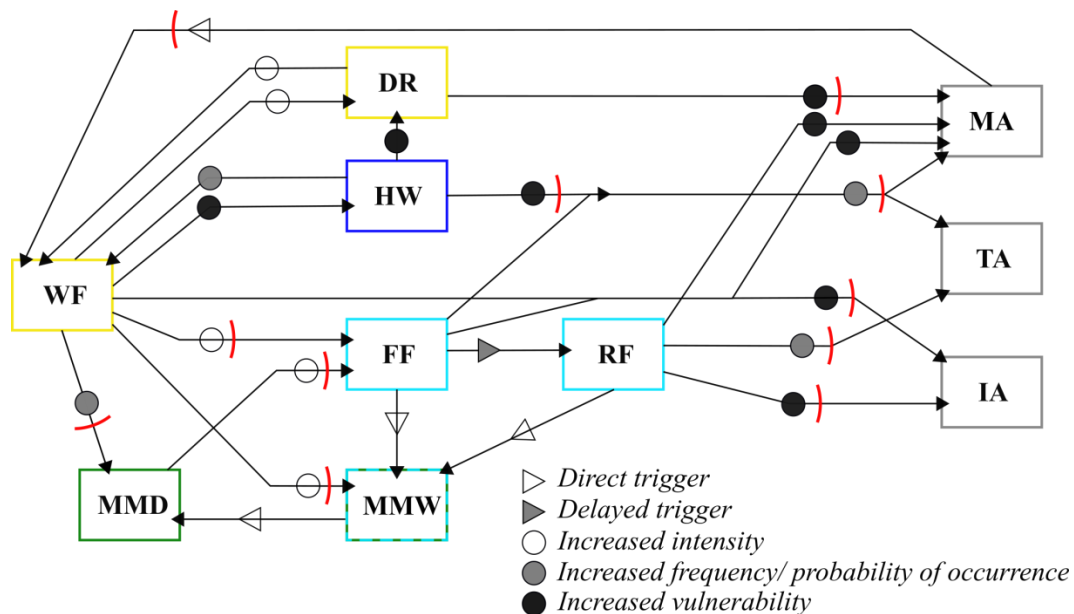


Fig. 4 : Chain of interactions for the preliminary multi-hazard risk assessment of wildfire in Ciotat. Hazard codes are presented in Tab. 1

Overall, the results show that significant interactions occur between wildfire and flooding and between wildfire in combination with extreme temperatures and vulnerable infrastructure. Probabilistic quantitative or semi-quantitative estimations (with and without measures of protection) are possible between the interactions of fire - flash flood - debris flow - urban flooding through methods such as fault and event trees, Bayesian networks and other. Indicators

of vulnerability assessments can be added to reinforce the semi-quantitative assessment with respect to the different levels of structural and human exposure. This methods are beyond the scope of this study that, so far, is limited to preliminary hazards maps for the scenario of wildfire in Ciotat as presented in the following.

Step 5: Mapping

The hazards identified in the interaction chain were mapped and subsequently overlapped to examine added exposure and thereafter the increased risk which might arise due to the specific scenario. Vulnerable zones and features were identified through in situ observations. Here the map of wildfire and flooding is presented along with several technological hazards that might arise (Fig. 5). The main causative conditions for fire in Ciotat are high temperatures and dry vegetation that is prone to combustion. The extent of various historical wildfires in Ciotat (shown in yellow) shows the impact of the Mistral winds, whose direction propagates the fire towards the south-east where the city is located. The identified vulnerabilities are the proximity to the high-risk zones and the dense vegetation surrounding some residential areas.

All rainwater from Fardeloup region west of Ciotat flows into the Roubaud valley that, in the urbanised zone is semi-artificial, partly underground and very badly maintained. Natural materials such as leaves, branches and grass tend to accumulate in the channel thus causing jamming (Fig. 6), which could occur in a bigger extent after a forest fire. Garbage thrown in the trench is also a frequently reported problem, evident also during the site inspection (several large items such as wood blocks, carts and even a mattress were spotted in the channel source). Flood zones of high and moderate risk have been mapped for the area but without taking into consideration the effects of jamming which might cause all the water to overtop and cause excessive damage to buildings and potentially people. Among the exposed elements-at-risk are a stadium and a high school but also various shops and a supermarket that gives high human impact potential.

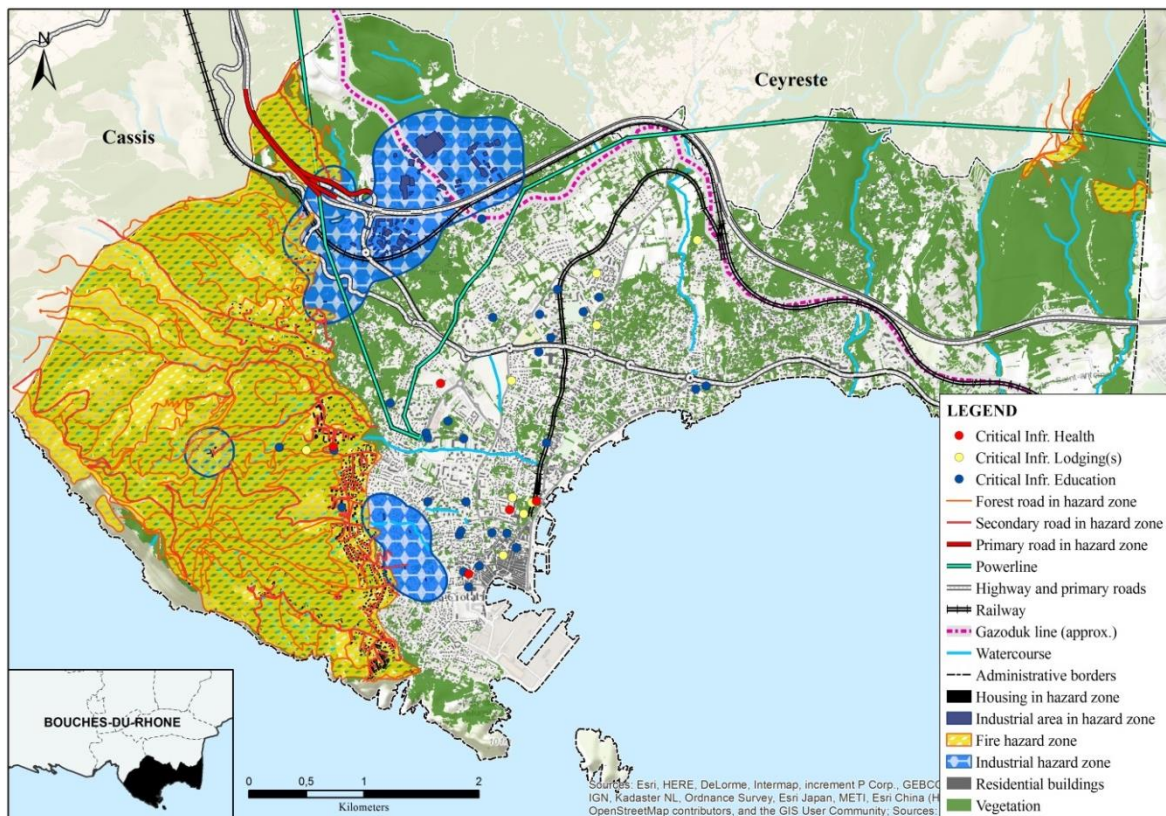


Fig. 5 : Map of wildfire and flood hazard for Ciotat.



Fig. 6: Vegetation accumulation at one of the underground sections of the channel.



Fig. 7: Map of the flood risk (red or high risk and blue for low risk) in Roubaud valley.

Another identified multi-hazard zone is the location of the industrial zone Athelia of Ciotat (shown in blue polka dots), which overlaps partly with the extent of wildfire risk. Within that extent is the highway, signalled as a zone of transport of dangerous materials (Ville de la Ciotat, n.d.) and the Gazoduk line.

The mapping process is an indispensable step in the multi-hazards risk assessment process since it focuses on the spatial extent of events and thus allows to move towards the semi-/quantification of the multi-hazards risk. For example, identified flood-prone zones allow assessing which riverbanks are prone to erosion according to their soil/slope characteristics. Furthermore, multi-hazards mapping can facilitate the risk management process as well. In our case study, the extent of wildfire hazard shows exactly which residential buildings are at high risk and in addition which are the safest axes for rescue and evacuation. In the aftermath of a fire, woody materials are expected to accumulate in small river channels and spatial analysis techniques can be used to estimate the increased risk of flooding in the case of an extreme precipitation. Specific precautions can subsequently be adopted (vegetation control around the perimeter, warnings etc.) to prevent the triggering of secondary hazard events and thus better risk management.

Conclusion

To summarize, a comprehensive approach to risk assessment in human-environment systems should be consisted not only of studying the naturally occurring hazards (Wisner et al., 2004) but also those of technological origin and the mutual interactions between either or both of these (Gill and Malamud, 2017, 2016). This work also underlines the importance of considering multiple types and forms of hazard interactions in a structured methodology that allows clear multi-hazards risk representation. Based on that stepping stone, preliminary assessment can be made and mitigative and protective non-structural measures can be enforced quickly. Lastly, the constructed chains of hazards show the data and expertise requirements for future semi-/quantitative risk estimation and possible structural protective measures. We aspire to implement the approach to other territories to validate it on cases possibly different according to hazards (and consequently interactions), elements at risk, and protective measures.

At this stage, the developed method rests conceptual and qualitative. It is envisioned that in the future a set of techniques will be developed for alternating between semi-quantitative to quantitative data, depending on the flux typology, that will allow more precise risk estimation under different scenarios. In the produced chain for example, warning issues for wildfires are already operational, therefore probabilistic assessment of fire could be made (in some uncertainty range) with an estimation of the fire extent, the loss of forest etc. GIS analysis of the slope and terrain can produce an estimation of potential landslides and debris material given the area that was burnt. Precipitation data can be analysed to forecast extreme events and flash floods and estimate the new extent of impact due to the loss of the forest. Finally based on the

new estimations and the additional amount of exposed elements-at-risk, damage costs and vulnerability indices can be generated to account for human exposure.

Acknowledgements

The authors would like to thank Pascal Di Maiolo for the organisation of the site inspection and his comments on the inspected area and Thomas Curt for providing the data and his comments related to historical fires in the area of Ciotat.

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