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Assessment of commuters' daily exposure to flash flooding over the roads of the Gard region, France

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SUMMARY

Flash floods are responsible for a majority of natural disaster fatalities in the USA and Europe and most of them are vehicle-related. If human exposure to flood is generally assessed through the number of inhabitants per buildings located in flood prone zone, it is clear that this number varies dramatically throughout the day as people move from place to place to follow their daily program of activities. Knowing the number of motorists exposed on flood prone road sections or the factors determining their exposure would allow providing a more realistic evaluation of the degree of exposure. In order to bridge this gap and provide emergency managers with methods to assess the risk level for motorists, this paper describes two methods, a simple rough-and-ready estimate and a traffic attribution method, and applies both of them on datasets of the Gard *département*, an administrative region of Southern France with about 700 000 inhabitants over 5875 km^2. The first method to obtain an overall estimation of motorists flood exposure is to combine (i) the regional density of roads and rivers to derive a count of potential road cuts and (ii) the average daily kilometers driven by commuters of the study area to derive the number of people passing these potential cuts. If useful as a first approximation, this method fails to capture the spatial heterogeneities introduced by the geometry of river and road networks and the distribution of commuters' itineraries. To address this point, this paper (i) uses a pre-established detailed identification of road cuts (Naulin et al., 2013) and (ii) applies a well-known traffic attribution method to existing and freely available census datasets.

Both methods indicate that commuters' exposure is much larger than the number of commuters itself, illustrating the risk amplification effect of mobility. Comparing the results from both methods shows that (i) the road network geometry plays a significant role in reducing the risk of river-road dangerous intersections and (ii) not all commuters are equally exposed. Evidently commuters who have longer routes are more exposed, but residents of rural municipalities as well as professionals with highly qualified jobs are also more exposed. Finally, these exposure assessment methods applied to the Gard area allows locating road sections where commuters' exposure to flood is high. It also sets the first step toward the implementation of a modeling platform able to combine the estimation of daily travel patterns exposure and behavioral response of motorists to road flooding, a critical input for emergency services and services in charge of the management of road networks in flash flood prone areas.

0. Introduction

Flash floods are responsible for a majority of natural disaster fatalities in the USA, Australia and Europe. Many studies investigating fatality circumstances have shown that more than half of the flash flood fatalities in these countries are vehicle-related (Duclos et al., 1991; Coates, 1999; Jonkman, 2005; Jonkman and Kelman, 2005; Drobot et al., 2007; Ashley and Ashley, 2008; Coates and Haynes, 2008), making mobility a primary cause of vulnerability during flash floods (Ruin, 2010). The question of people's motivation and circumstances for driving into flooded roads have been addressed by many researchers in the last ten years (Drobot et al., 2007; Ruin et al., 2007, 2008; Coles, 2008; League, 2009; Maples and Tiefenbacher, 2009; Sharif et al., 2012; Diakakis and

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Deligiannakis, 2013; Spitalar et al., 2014; see Becker et al., 2015 for a literature review on the subject). These studies identified several factors as age, gender and experience, suggesting that younger male drivers (under 35) often underestimate the risk of driving into flooded roads (Drobot et al., 2007; Ruin et al., 2007). Familiarity with the route and maintaining normal daily activities, especially commuting to work is also an important factor of risk taking behavior around floodwater (Coates, 1999; Coates and Haynes, 2008; League, 2009; Maples and Tiefenbacher, 2009; Ruin et al., 2009). Finally and with respect to the previously cited factors, the analysis of flash flood vehicle-related fatalities shows that middle-aged men are more prone to such fatal accidents but whether it is a question of "active[1]" or "passive" behavior is not clear yet (Terti et al., 2015b). In fact, not much is known about the chance that behaviors of exposed people lead to fatalities, a useful information to allow road and emergency managers to assess the risk level or the mortality and to design protection strategy accordingly. In order to address this question we need to know how much of the road traffic is concerned and which types of daily commutes and commuters are more exposed to flash flood risk. At present, mobility aspects are not much taken into account when assessing human exposure and vulnerability to natural hazards. Most of the time, resident population density data is used assuming a static distribution, which contrasts with the fast dynamics of the flash flood phenomenon. Recently, Terti et al. (2015a,b) showed that daily and sub-daily variation of population distribution may provide a more accurate and appropriate assessment of human exposure to flash flood. Several studies in transportation research focused on road network vulnerability to adverse weather conditions (Koetse and Rietveld, 2009). Different methods were developed in order to identify critical road segments where disruptions would lead to severe consequences. Berdica (2002) defined road segments vulnerability as a function of the probability of occurrence of a hazardous event and the importance of related impacts in term of serviceability of road links. Jenelius (2009) introduced the concept of link criticality quantifying the road network vulnerability by measuring the increase of global travel cost when these links are closed. Versini et al. (2010) and Naulin et al. (2013) proposed a system intended to evaluate road inundation risks based on high spatial and temporal resolution rainfall estimates in the Gard region (5875 km^2) in southern France. They used an extensive inventory of road submersions over the last 40 years in order to rate the susceptibility of roads flooding at points where the hydrographic network intercepts the road network. Our approach is complementary to this study as it aims at introducing the human exposure component in the risk evaluation.

While those studies focus on the sensibility of the road segments and potential impacts on the network functioning, journey-time exposure of road users have been mostly addressed by studies dealing with traffic-related air pollution (Gulliver and Briggs, 2005; Beckx et al., 2009). In this purpose, activity-based approach offers an appropriate framework to simulate individual travel-activity patterns. These activity-based models consider travel behavior as derived from the demand of activity participation and aim at predicting the sequence of activities conducted by individuals (McNally, 2000). In this paper, we consider that professional and school activities are the main purposes for daily commutes (return trip) and risk taking behavior when facing flooded roads. In fact, those regular and foreseeable activities are strong constraints of the week-day schedules of the 70%[2] of the Gard inhabitants who commute. According to a questionnaire survey made in 2004 on a sample of 960 Gard residents, professionals with daily work constraints are less willing to cancel their travels when a flash flood watch or warning is announced than non-workers (Ruin, 2010). Therefore, the present study proposes to assess the number and socio-demographic characteristics of the commuters whose daily routes cross potential road-flooding points (road cuts) as defined by Versini et al. (2010) and refined by Naulin et al. (2013). We consider that commuters who cross the most potential road-flooding points are the most exposed. Identifying the characteristics of the most exposed commuters is a necessary first step toward understanding if the most exposed are also the most vulnerable or if individual's coping capacity plays a significant role in lessening vehicle-related flash flood losses.

This paper compares two methods to evaluate daily mobility exposure to flood hazards by using existing and freely available datasets. A first rough-and-ready method derives counts of road–river intersections (road cuts) and average daily kilometers driven by commuters from standard bulk statistics from the study area. The second more elaborated method uses, on the one hand, the road flooding susceptibility established by Naulin et al. (2013) and, on the other hand, a classical traffic attribution method affecting commuters to plausible travel routes and to potential road flooding points after origin-destination disaggregated census data. The methodology proposed is generic and could be extended to other regions provided with the same type of data. To our best knowledge, comparable studies are seldom (see road exposure considerations about avalanches in Zischg et al., 2005).

The study concerns a region of southern France characterized by a typical Mediterranean climate with heavy rainfall events triggering severe flash floods during the autumn season (Delrieu et al., 2005; Gaume et al., 2009). According to Delrieu et al. (2005), Gard's climate gathers the three necessary ingredients to trigger large amounts of precipitation during several days but also within a few hours in the case of Mesoscale Convective System (MCS): (i) proximity of the Mediterranean sea as a reservoir of energy and moisture, (ii) a southerly flow that both advects and destabilizes air masses from the Mediterranean sea toward the coast, (iii) the surrounding relief of the Alps, *Pyrénées* and *Massif Central* mountains slows down and enhances perturbations. These elements may result in very localized or much larger disastrous flash flood events.

Since 1225, the Gard region suffered 506 floods, with 66% of the 353 municipalities cumulating at least 10 referenced flood events including some that were affected more than hundreds times (CG30, 2015). Between 1316 and 1999, Antoine et al. (2001) recorded 27 fatal flood episodes and 277 deaths in the Gard. Since 1999, five fatal events added about 30 casualties to the toll. In 2013, 50% of companies and 35% of inhabitants of the Gard area were located in flood prone zone. In addition, previous studies have shown that not only the Gard region is particularly sensitive to road flooding but also that flash flood risk is often underestimated by the population, specially when related with daily mobility and motor vehicle usage (Ruin et al., 2007; Versini et al., 2010).

Section 1 describes the dataset used and introduces some terminology and mathematical expressions. At the end of the article, a section details the notations used in the different formulas and the corresponding terminology. Section 2 proposes a first rough-and-ready approximation of the exposure based on basic data and simplified calculation. Section 3 introduces the methodological basis of a refined exposure assessment using traffic attribution of census datasets. Sections 4 and 5 examine the results from the traffic attribution method in order to test the hypothesis that all commuters are not equally exposed. Section 6 gives concluding comments.

[1] As defined by Coates (1999), "active" behavior means that *"rather than just happening to be in the wrong place, or trying to escape the flood, they were actively pursuing their line of employment, a reflection, possibly, of a more aggressive work environment*".

[2] According to the 2006 INSEE census dataset.