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Assessment of the susceptibility of roads to flooding based on geographical information – test in a flash flood prone area (the Gard region, France)

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Abstract. In flash flood prone areas, roads are often the first assets affected by inundations which make rescue operations difficult and represent a major threat to lives: almost half of the victims are car passengers trapped by floods. In the past years, the Gard region (France) road management services have realized an extensive inventory of the known road submersions that occurred during the last 40 years. This inventory provided an unique opportunity to analyse the causes of road flooding in an area frequently affected by severe flash floods. It will be used to develop a road submersion susceptibility rating method, representing the first element of a road warning system.

This paper presents the results of the analysis of this data set. A companion paper will show how the proposed road susceptibility rating method can be combined with distributed rainfall-runoff simulations to provide accurate road submersion risk maps.

The very low correlation between the various possible explanatory factors and the susceptibility to flooding measured by the number of past observed submersions implied the use of particular statistical analysis methods based on the general principals of the discriminant analysis.

The analysis led to the definition of four susceptibility classes for river crossing road sections. Validation tests confirmed that this classification is robust, at least in the considered area. One major outcome of the analysis is that the susceptibility to flooding is rather linked to the location of the road sections than to the size of the river crossing structure (bridge or culvert).

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1 Introduction

Road network and traffic monitoring are often major issues for flood event managers. Anticipating the state of a road network during floods can be helpful to prevent traffic using roads at risk and identify the safest access routes to the affected areas for rescue services. This is particularly true for flash flood prone areas where a large amount of victims are passengers trapped in their cars by the rapid rise of water on inundated roads (Drobot et al., 2007; Ruin et al., 2007; Jonkman, 2005; Jonkman and Kelman, 2005).

An accurate forecast of the location of flooded road sections should be based on both: a reliable estimation of the natural hazard inducing the inundation (river flood or local surface runoff magnitude) and also an evaluation of the susceptibility to flooding of each exposed road section. The term "susceptibility" has been preferred to the more general term "vulnerability" which often involves an explicit and quantitative evaluation of the consequences of a natural hazard (Douglas, 2007; Schuster and Fleming, 1986; Fuchs et al., 2007). The susceptibility describes hereafter the likelihood of a road section to be flooded given the natural hazard: the frequency of flooding of the considered the road section over a long period of time. A companion paper (Versini et al., 2010) will present an approach for the estimation of the flood magnitude for a large number of catchments over a region and the combination of this magnitude and of a susceptibility rate to compute a flood risk index for the road sections. This work is also presented in detail in a research report (Lumbroso et al., 2007) of the FP6 European Research project FLOODsite. This paper focuses specifically on the development and validation of the first element of this risk assessment tool: the road section susceptibility to flooding rating method.

The main scientific question was whether it is possible to have a prior knowledge of the susceptibility of the roads to flooding on the basis of various sources of data concerning

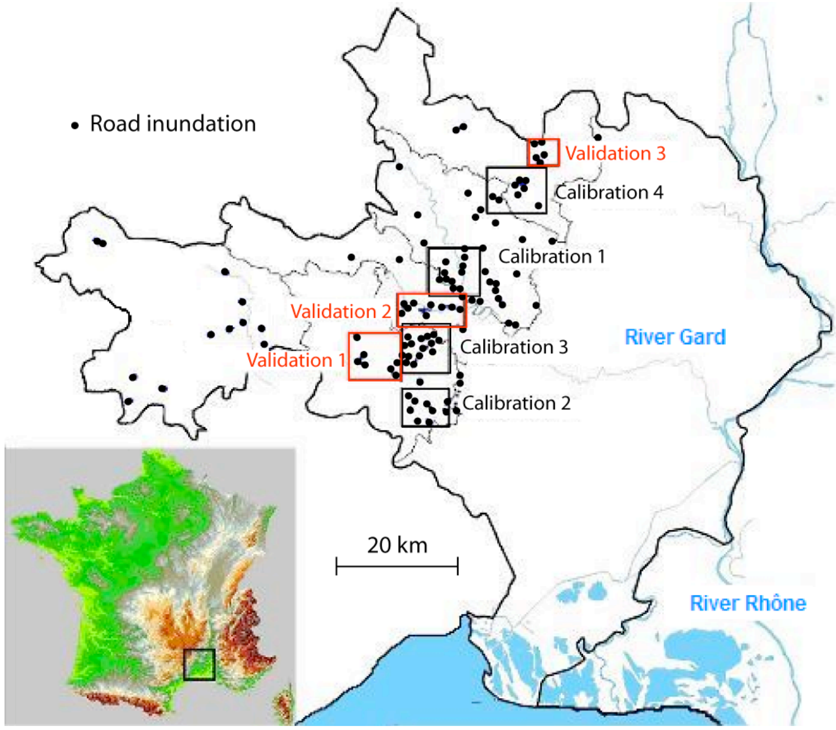

Fig. 1. The Gard Region, the four calibration (black rectangles) and the three validation areas (red rectangles) and the location of the road inundations reported in the PICH database.

the road network and the considered area. Is for example possible to identify the most frequently affected sections? To do so, it is necessary to establish what the specific characteristics of the most affected points are on which a susceptibility rating could be based. The determination of these specific characteristics and the development of the rating method were the main issues of this research.

Until now, little work has been conducted on the impact of natural hazards on networks and particularly road networks (Dalziell and Nicholson, 2001; Franchin et al., 2006; Guzzetti et al., 2004). Local susceptibility to flooding studies are often conducted for the purpose of bridge or culvert design for instance. Some few studies may have concerned particularly exposed itineraries where a typical hazard may occur: avalanche (Margreth et al., 2003; Zischg et al., 2005), or inundation (Geoplus, 2004) for example. But to our knowledge, no study or research has attempted to characterize systematically the susceptibility of roads to flooding at a regional scale. The lack of observations concerning road flooding, necessary for the calibration and validation of a susceptibility characterization method, has long been a limiting factor for such studies.

Recently, in relation to the recurrent problems of road inundations and especially to the dramatic consequences of the 2002 extreme flash-flood event (Delrieu et al., 2005; Gaume and Bouvier, 2004), the Gard road management services decided to conduct an inventory of the known road submersions during the last 40 years (Lignon, 2004). The resulting dataset called PICH (Plan d'Intervention aux Crises Hydrologiques) including the exact location of the submerged points and often the number of observed inundations gave us the unique opportunity to analyse the aforementioned questions (see next section for a detailed presentation).

This paper presents the analysis methodology of the PICH dataset, the proposed susceptibility rating method resulting from this analysis and some validation and extrapolation tests.

2 The Gard region and the PICH inventory

The Gard region (Fig. 1), located in the south of France, covers about 3000 km^2 on the right-hand side of the Rhône river valley. The South-Eastern half of the area comprises calcareous plateaus located at altitudes ranging from 50 to 300 m a.s.l., while the North-Western half is mountainous with various bedrocks and reaches 1700 m a.s.l. at its highest point. The Gard region has a typical Mediterranean climate characterized by frequent and very heavy storm events occurring especially in autumn. The 10-year return period daily precipitation exceeds 100 mm on the plateaus and 150 mm in the mountainous part of the area (CNRS/INPG, 1997). Local storm events often produce hundreds of mm within a few hours. A maximum 24-h precipitation exceeding 600 mm was observed on 7 October 2002. During the same storm event, a total area of about 3000 km^2 received more than 300 mm within less than 24 h (Gaume and Bouvierm 2004; Delrieu et al., 2005). This rainfall regime explains that the Gard region belongs to the areas in Europe affected by the most frequent and severe flash floods (Gaume et al., 2009). During these floods, roads are often flooded. Significant road flooding occurs at least once a year on average. The monitoring of the road network during flash flood events is therefore a major issue for the rescue services. 40% of the victims of floods in the Gard during the last 50 years were motorists (Antoine et al., 2001). More recently, about 200 emergency vehicles were seriously damaged or destroyed by the flows during the extreme September 2002 floods (Delrieu et al., 2005; Ruin et al., 2008).

The PICH is an inventory of the road submersions over the last 40 years. It has been developed by the state services in charge of the maintenance and management of the road network (Lignon, 2004). The objective of PICH was to collate the experience gained by employees of these services that would be useful for the management of the road network during flood events. Based on the employees' experience and memory, this inventory covers the western and central part of the region, shown in Fig. 1. This comprises the upstream parts of the river catchments. These are the areas that are exposed to flash floods. This part of the region is still a mainly rural area with an average population density of 106 people/km^2.

The PICH inventory provides a comprehensive database, especially for the central part of the region, essentially rural, where the submersions of roads are most frequent. It contains the exact locations of 167 road sections flooded during the last 40 years over the total length of 2500 km of the main road network. In 75% of the cases, the number of inundations is known, providing an estimate of the submersion frequency (Fig. 2). Almost half of the listed road sections have suffered more than 20 floods during the last 40 years, which means a inundation frequency greater than one every two years.

The road sections inventoried in the PICH can be classified into three categories: i) river crossings (78% of the total), ii) low points where runoff water accumulates on roads during storm events (13%) and iii) road sections adjacent to a river in a flood plain (9%). In the following, the road sections inventoried in the PICH are simply denoted as PICH road sections or PICH points.

The number of PICH road sections and their submersion frequencies are to be related to the very high flood hazard in the region. In the French Mediterranean area, the 10-year return period peak discharge for a 10 to 500 km^2 catchment is generally of the range of 1 to 2 m^3/s/km^2 (Gaume et al., 2009; Gaume et al., 2004; Payrastre et al., 2005). This is much higher than the 100 years return period flood of catchments with equivalent areas in other regions of France or Europe. River crossing structures can hardly, from a technical and economical point of view, be designed to carry the extreme Mediterranean floods.

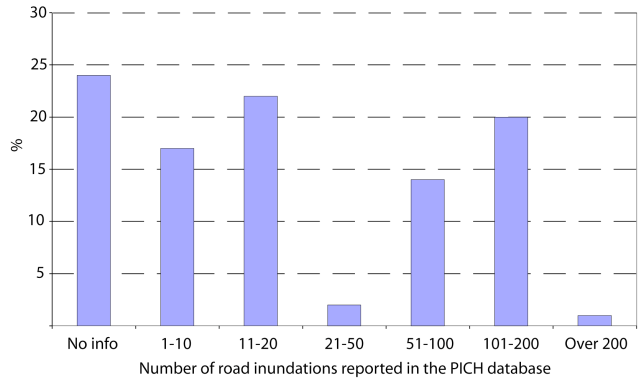

Fig. 2. Distribution of the number of reported inundation events during the last 40 years in the PICH database.

3 Methology of analysis

This section describes the methodology that has been applied to identify the factors affecting the road susceptibility to flooding and to calibrate a susceptibility rating method. It consistent into three steps: 1) identification of the set of all the road sections possibly exposed to flooding largely exceeding the PICH inventory, 2) identification of the specificities of the PICH road sections, and 3) definition of a susceptibility rate.

3.1 Calibration and validation strategy

The PICH inventory covers two different regions in which the densities of the PICH points are contrasted. The Western and Northern part of the area corresponds to the upstream catchments of the river systems. It is mountainous and less populated. The number of the inventoried PICH points is limited and not sufficiently high to support the development of a susceptibility rating method (Fig. 1). The analysis has therefore been focussed on the central part of the region where the PICH inventory is more comprehensive. This area has been further divided into sub-areas (rectangular windows on Fig. 1) to keep one part of the dataset for the validation of the proposed rating method and to be able to test the robustness of the analyses and hence their possible extrapolation to other areas.

3.2 Identification of the potentially flooded road sections

According to the PICH inventory, the points exposed to flooding are of three different types: river crossings, low accumulation points, and river adjacent points that can be submerged during river overbank flow events. The first step of the analysis consisted of identifying all the points of the road network belonging to one of these categories based on the available road and river network GIS layers and on a 50 m×50 m (IGN, 2005) digital terrain model (DTM). This

Table 1. Identification of the potentially flooded points in the calibration and validation windows.

	Number of identified road sections	Number of PICH road sections	Number of PICH road sections in the identified set
Section points	293	54	54
Low points	158	9	7
Bordering points	81	6	1

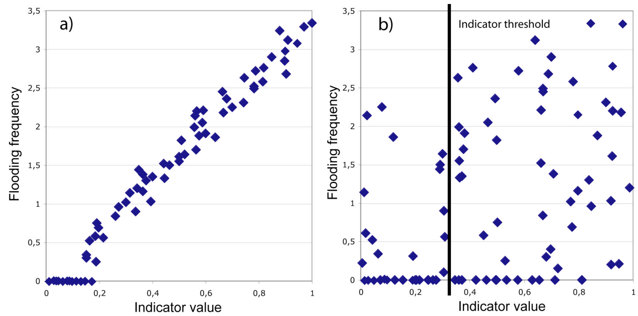

Fig. 3. Relation between the flooding frequency and the indicator values in an ideal case where a regression approach would be useful **(a)** and the actual situation **(b)**.

coarse resolution is generally the only one available over large areas. Geographical information was processed using the open source GIS GRASS (Neteler and Mitasova, 2004). To facilitate the computation of local characteristics, the DTM has been re-interpolated to a 25 m resolution with a Regularised Spline with Smoothing and Tension method (Mitasova and Mitas, 1993). Steps and flat areas resulting from the discrete nature of the elevation data were also smoothed out. This does not improve the DTM data but facilitates their processing for the identification of morphological features such as valleys and shoulders (Rousseaux, 2006).

All river crossings were identified using existing river and road network GIS layers. Different methods were tested for the identification of the low accumulation points (formulas combining upstream drainage area and local slope), and of the river bordering points (formulas combining their distance from the river and the difference in altitude between the road and the river). Table 1 summarizes the best results obtained for the calibration and the validation areas. All the river crossings inventoried in the PICH are identified. It is worth noting that about one fifth of the river crossings in the considered areas are listed in the PICH. Conversely, if we consider that the PICH inventory is close to comprehensive, 20% of the river crossings – the PICH sections – have an inundation empirical return period smaller than 40 years. The number and the flooding frequency of PICH sections as well as the contrast with the empirical flooding return period of the other sections – i.e. more than 40 years – are favourable elements to reveal the specific conditions leading to a high susceptibility to flooding.

As for the low points and river bordering points, their identification appears much more uncertain on the basis of the DTM: the proportion of identified points which do not belong to the PICH, Non-PICH points, is much larger and it is not possible to retrieve all the PICH points from the analysis of the DTM, especially for the bordering points. In some cases, the susceptibility of the points seems to be linked to very local settings that are not detectable on the DTM: low point of an embankment or a misconception of a ditch for instance. A systematic approach for the identification and the rating of the susceptibility of these points seems not practicable on the basis of the standard coarse DTM available (a ditch is a meter wide). In a risk assessment tool, their susceptibility to flooding will have to be defined individually for each point based on past experiences, which is possible according to their limited number. They were not considered in the rest of the analysis, focused on the susceptibility assessment of the river crossing sections.

3.3 Identification of the factors affecting the susceptibility of roads to flooding

The explanatory factor identification method and the subsequent rating method have been selected on the basis of the data type and of the data set structure. A large variety of possible explanatory factors has been tested as will be illustrated in the next sections. In all the cases, the correlation between the values of the considered factor and the flooding empirical return period (available measure of road susceptibility to flooding) appeared extremely weak (correlation coefficients around 0.1). This state of facts disqualifies the standard analysis of variance and linear or non-linear regression approaches (Fig. 3). Moreover, the information available on the susceptibility to flooding is partly qualitative: the flooding return period is unknown for 25% of the PICH points and for all the Non-PICH points. The discriminant analysis appeared therefore as the best suited type of approaches for the development of a susceptibility rating method with only two classes because the size of each class must be sufficient to enable statistical tests. The two classes are:

- The non-PICH points: flooding return period larger than 40 years for most of the elements of this class with some exceptions possibly due to sampling fluctuation and some missed floods in the PICH inventory.
- The PICH points: empirical flooding return period lower than 40 years.

Table 2. Illustration of the efficiency of a sorting based on the discharge ratio.

Suscepti-bility class	Threshold values	Selected sub-set			
		Selected PICH	Selected Non-PICH	Selected total	PICH/ Total class
1	0.09	20%	2%	11%	90%
2	0.34	30%	16%	23%	63%
3	0.89	50%	62%	56%	42%
4		0%	20%	10%	0%

Table 3. Illustration of the efficiency of a sorting based on the altitude.

Suscepti-bility class	Threshold values	Selected sub-set			
		Selected PICH	Selected Non-PICH	Selected total	PICH/ Total class
1	0.12	20%	6%	12%	70%
2	0.28	30%	8%	17%	72%
3	0.94	50%	79%	67%	30%
4		0%	7%	4%	0%

The first step of the discriminant analysis consists in identifying the factors linked to the susceptibility to flooding (discriminant factors). Their statistical distribution in the PICH class should differ significantly from their statistical distribution in the Non-PICH class. A Wilcoxon-Mann-Whitney test has been used to compare these distributions.

In addition to this test, the discriminatory power of the factors is evaluated through a sorting test and summarized in a table (see Tables 2 to 7). This sorting test prefigures the final susceptibility rating method. Threshold values for the considered factor are adjusted to define four susceptibility classes that are:

- Susceptibility class 1: contains 20% of the PICH points and as few as possible Non-PICH points.
- Susceptibility class 2: contains an additional 30% of the PICH points.
- Susceptibility class 3: contains the 50% of the remaining PICH points.
- Susceptibility class 4: contains only Non-PICH points.

The proportions of Non-PICH points should be zero for the first 3 classes if the selected factor enables a perfect discrimination between PICH and Non-PICH points; they are

Table 4. The sorting efficiency based on the local slope.

Suscepti-bility class	Threshold values	Selected sub-set			
		Selected PICH	Selected Non-PICH	Selected total	PICH/ Total class
1	0.13	20%	9%	14%	60%
2	0.33	30%	12%	19%	63%
3	0.95	50%	72%	63%	30%
4		0%	7%	4%	0%

Table 5. Sorting efficiency based on the upstream watershed area.

Suscepti-bility class	Threshold values	Selected sub-set			
		Selected PICH	Selected Non-PICH	Selected total	PICH/ Total class
1	0.12	20%	5%	11%	73%
2	0.33	30%	15%	20%	61%
3	0.98	50%	82%	69%	30%
4		0%	0%	10%	0%

Table 6. Sorting efficiency based on the proposed indicator combination.

Suscepti-bility class	Con-nector	Thres-hold values	Selected sub-set			
			Selected PICH	Selected Non-PICH	Selected total	PICH/ Total class
1	AND	0.3	20%	2%	8%	100%
2	AND	0.57	30%	17%	22%	54%
3	OR	0.57	50%	58%	54%	35%
4			0%	25%	16%	0%

Table 7. Validation of the susceptibility rating method.

Suscepti-bility class	Threshold values	Selected sub-set			
		Selected PICH	Selected Non-PICH	Selected total	PICH/ Total class
1	0.09	14%	14%	5%	61%
2	0.34	33%	33%	18%	51%
3	0.89	53%	53%	54%	35%
4		0%	0%	15%	0%

the same as for the PICH points if no sorting is possible. The adjustment of the susceptibility rating method will mainly aim at reducing the proportion of Non-PICH points in the first 3 classes of susceptibility.

Two more details are to be given on this phase of the analysis. First, the range of values for the various possible discriminant factors (altitudes, slopes…) may vary from one area to another. To be able to compare results obtained in different calibration areas and to extrapolate the results to the validation areas, it was necessary to normalize the values of some of the factors in each tested area. The chosen normalized factor or index (Ind) corresponds to a probability of exceedance:

$$\mathrm{Ind} = \frac{i-0.5}{n+0.5} \tag{1}$$

if PICH point values have a tendency to be among the lowest values

$$\mathrm{Ind} = 1-\frac{i-0.5}{n+0.5} \tag{2}$$

if PICH point values appears among the highest values

where i is the rank of the value in the area where all the values have been sorted in increasing order and n is the total number of values (potentially flooded road sections) in the considered area. Note that the normalization method has been adjusted so as to affect the lowest factor values to the PICH points. This normalisation method has been chosen for its robustness especially to extreme values.

The reported flooding frequencies of the PICH points, when available, are not used in the analysis and calibration phase. This information will serve during the validation phase: if the proposed classification method is consistent, the frequently flooded points must be concentrated in the highest susceptibility classes. This will be verified at the final validation stage.

3.4 Adjustment of a susceptibility rating method

The discriminatory powers of each individual tested factor proved to be limited. To increase the sorting efficiency, combinations of factors were tested. The classes can be delimited by thresholds corresponding to a linear combination of the factor values (Fig. 4a) or by threshold values that should be simultaneously exceeded by the factor values – connector "and" – or exceeded by one factor value at least – connector "or" (see Fig. 4b). According to the structure of the data set, a non-linear combination based on the logical connectors "and" and "or" appeared to be more suited than the traditional linear combination of the values of the factors to reach the best classification efficiency. The difference between the two approaches is nevertheless limited.

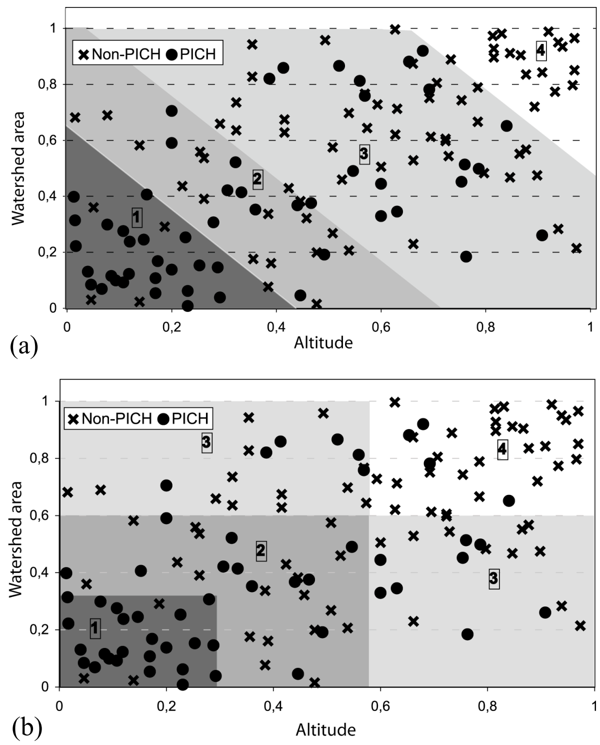

Fig. 4. Illustration of the separation of a data set into four classes based on a combination of two factors, the coverage of the classes 1 to 4 appear in grey gradation: **(a)** thresholds limiting the classes equal to a linear combination of factors and **(b)** combination of thresholds with connectors "and" (classes 1, 2 and 4) and "or" (class 3).

4 Analysis of the susceptibility of road sections to flooding

4.1 Susceptibility and design of the river crossing structures

It is natural to think that the susceptibility of a road to flooding may be linked to the dimensions of the river crossing structure (bridge or culvert) and more specifically to the adequacy between the opening – cross-section – of this structure and the discharges that may be produced by the upstream watershed during floods.

The first tested factor aimed at characterizing this adequacy. It relies on the comparison of two different discharge values:

– The theoretical maximum free surface discharge capacity through the crossing structure Qc that can be estimated using the Manning-Strickler formula (Ven Te Chow, 1964) if the shape and dimensions of the structure's opening is known:

$$Q_{\mathrm{c}} = K \cdot Rh^{\frac{3}{2}} \cdot I^{\frac{1}{2}} \cdot S \tag{3}$$

K is the roughness coefficient taken constant equal to 50, *Rh* is the hydraulic radius, I is the local slope computed using the digital terrain model, and S is the cross-sectional area of the opening.

– The theoretical 10-year return period discharge for the upstream watershed, based on a well established formula adapted to small catchments in France – the Crupedix formula (CEMAGREF, 1980) – which has proven to be reliable, especially in the considered area (Estienne and Roche, 1994):

$$Q_{\mathrm{c}} = K \cdot Rh^{\frac{3}{2}} \cdot I^{\frac{1}{2}} \cdot S \tag{4}$$

where A is the catchment area in km^2, P_{j10} is 10-year daily rainfall in mm, estimated using a local monograph (CNRS/INPG, 1997) and R is a regional parameter equal to 1.5 for the Gard Region.

The discharge ratio Q_{10}/Q_{c} has been computed for all the road sections for which the dimensions of the river crossing structures were available. The distribution of these discharge ratios for the PICH and Non-PICH datasets is shown in Fig. 5.

The two distributions are significantly different; there is, in particular, a higher proportion of large values of the ratio in the PICH data set. Nevertheless, this ratio is not very discriminatory: more than 60% of the PICH sections are characterized by a discharge ratio lower than 1 (theoretical return period of flooding larger than 10 years). It is important here to recall that a large majority of the PICH points have empirical flooding return period smaller than 10 years (see Fig. 2). The discharge ratio is poorly correlated with the empirical flooding return period of the PICH sections (coefficient of correlation equal to 0.05).

The modest performances of this first tested factor can be attributed to the inaccuracy of both computed discharge values and of the resulting ratio. But it is the best that can be done to characterise the capacity of river crossing structures based on commonly available information. The inaccuracy is nevertheless not the only explanation. A detailed analysis of some recently flooded roads – based on field surveys and technical reports (GEOPLUS, 2004) – has revealed that the crossing structure itself is rarely submerged but rather a low point of the road when it crosses a floodplain. Inundations may occur even if the river crossing structure is well dimensioned as soon as the road has to run across a flood plain. This leads to think that the susceptibility to flooding may as well be explained by the location of the road sections. A susceptibility rating method based on geographical information would have another major advantage. Geographical information is easily available on a large territory, while the geometry of the river crossing structures is generally only known for a limited number of structures.

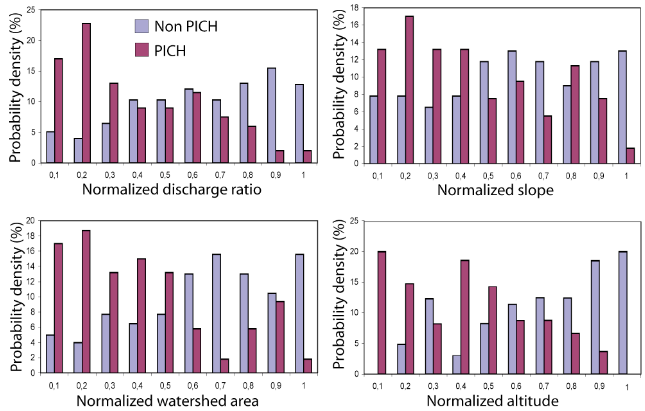

Fig. 5. Distribution of the some discriminant factor values for the PICH and Non-PICH sets in the four calibration areas.

4.2 Analysis of other possible explanatory factors

A large variety of possible discriminant factors based on geographical information has been analysed:

– local topographical indicators characterising the road section including altitude, slope, shape, and topographic wetness index (Beven and Kirkby, 1979),

– characteristics of the upstream catchment including area, land use, bed rock type, average altitude, average slope, and topographic wetness index distribution.

The Institut National de la Recherche Agronomique soil data base (INRA, 2000) has been used as source of information on the soil types and bedrock of the upstream watershed of each studied section. The initial complex classification has been simplified into five main categories of bedrocks and associated soils in the Gard Region. The Corine Land Cover database (IFEN, 2000) provided information on land cover. Again, the complex land use classification has been simplified and five classes defined: urban areas, agricultural land, forest, scrub and water bodies. A watershed is characterised by the proportion of area covered by each bedrock, soil and land use type.

The susceptibility of a road section to flooding did not appear to be significantly linked to the dominant land use type of its upstream catchment, nor to the soil bedrock types. A significant difference between the PICH and Non-PICH distributions according to the Wilcoxon-Mann-Whiley test appeared only for three factors: the road altitude, the local slope and upstream catchment area.

4.2.1 Susceptibility and altitude

The distribution of the normalized altitudes of PICH road sections in the four calibration regions differs significantly from a uniform distribution. This is shown in Fig. 5. The PICH road sections appear to be located in the lowest zones.

Around 40% of the PICH road sections lie in the 20% lowest parts of the calibration areas. Table 3 shows the sorting efficiency based on the altitude indicator value which is comparable to the efficiency obtained with the discharge ratio (see Table 2): the sorting efficiency is higher for the high susceptibility classes and lower for the low susceptibility classes.

4.2.2 Susceptibility and local slope

The second indicator extracted from the DTM that appeared to be linked to the susceptibility of the road is the local maximum slope around the considered road section. This slope indicates if the road section is located on a flat or a steep surface. It is therefore partly linked to the altitude. It can also characterize the local runoff: the flow velocities and hence the through-flow capacity of culverts may increase with the stream's slope. Figure 5 shows that a large number of the PICH road sections are located in flat areas. Approximately 60% of the PICH road sections belong to the 40% of the total set of potentially flooded sections with the lowest slopes. The sorting efficiency based on the local slope (Table 4) is slightly lower than when the altitude is used (Table 3). Still, the two lower susceptibility classes contain almost 80% of the Non-PICH sections.

4.2.3 Susceptibility and upstream watershed area

The catchment areas have been sorted in decreasing order so that the largest areas correspond to the lowest values of the normalised area indicator. The upstream catchments draining to the PICH road sections are generally larger than the catchments draining to the Non-PICH road sections. This is shown in Fig. 5. Inside the calibration areas, the average area of the PICH catchments is 30 km^2 whereas a Non-PICH catchment has an average area of 10 km^2.

The sorting out of the PICH road sections based on the value of the upstream catchment area indicator is far from perfect (Table 5) but appears as discriminant as the two previous indicators.

5 Proposal and evaluation of a susceptibility rating method

The comparison of the PICH and Non-PICH sub-sets reveals that four indicators are significantly linked to the susceptibility of a road section to flooding. The most efficient indicator seems to be the ratio between the 10-years peak discharge and the design discharge of the structure that crosses the river. Unfortunately, the geometry of the bridges and culverts is only available for a limited number of sections. As a consequence, this indicator can hardly be generalized over the whole region without a significant additional data collation effort.

Three indicators calculated from geographical data, available for every road section, display significantly different distributions for PICH and Non-PICH sections: altitude, local slope and area of the upstream catchment. As these indicators are only partly correlated, the sorting efficiency of the PICH and Non-PICH points could be improved by combining them.

5.1 Adjustment of the combination in the calibration areas

According to the normalization presented in Sect. 4, the indicators take their values in the range of 0 to 1. For the sake of simplicity, the three indicators have been combined using simultaneously the same threshold value to remain simple and robust. Using the same methodology previously used for each individual indicator, three thresholds delimiting four classes of susceptibility were defined based on the proportion of PICH sections in each class (20%, 30%, 50%, 0%). The two possible connectors AND and OR for the combination of the indicators have been tested. Figure 6 shows the cumulative distributions of exceedance of the combinations of indicators in the PICH and Non-PICH data sets. The vertical distance between the two distributions reveals the power of discrimination of the combination. The connector AND appears as better suited to define the high susceptibility classes while the connector OR has higher performances for the low susceptibility classes and enables the definition of a class containing no PICH points. The resulting sorting efficiencies are summarized in Table 6 for the four calibration areas.

The efficiency of the combination of indicators outperforms the sorting efficiency of any of the previously tested single indicators, confirming the complementarity between the selected indicators and the usefulness of their combination. Nevertheless, the indicators and their combination have been adjusted on four limited calibration areas. Is it robust? Will similar sorting efficiencies be obtained on the three validation areas? Moreover, are the observed flooding frequencies consistent with the susceptibility classes which have only been defined based on the PICH data set membership? This has been tested in the validation phase which results are presented hereafter.

5.2 Validation

The indicators combination method has been tested on the three validation areas (see Fig. 1) of the region. They contain 28 PICH sections for a total number of 112 sections. In each area, the following steps were applied: (i) calculation of the indicator values for each road section (i.e. altitude, local slope and catchment area), (ii) sorting out of the values by increasing order and computation of the normalised indicator values, (iii) application of the combination

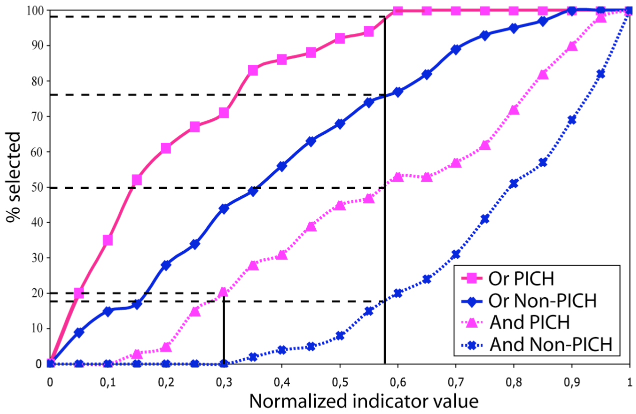

Fig. 6. Cumulative distributions of the combined index value for the two tested connectors for the PICH and Non-PICH sets in the four calibration areas.

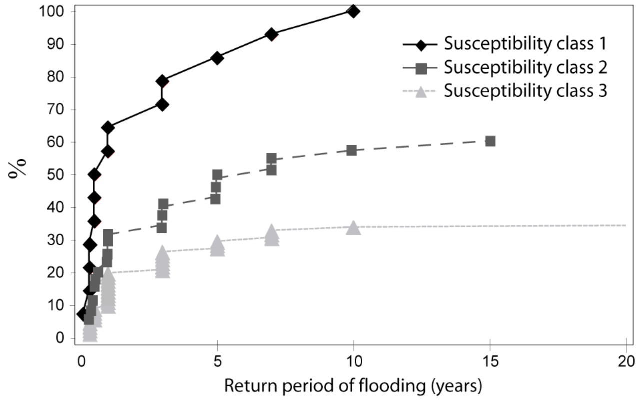

Fig. 7. Distribution of the empirical return periods of flooding for the PICH points of the various susceptibility classes.

Fig. 8. Example of a submerged access road to the river crossing structure located in the flood plain (Gard 2002 flood upstream the town of Sommières).

method as previously described, and (iv) allocation of each point to a susceptibility class. The results are shown in Table 7.

For the three validation areas, the sorting efficiencies are very similar to the ones obtained in the calibration areas, except for the susceptibility class 1 where the sorting efficiency is lower. This is an extremely satisfactory result. It should nevertheless be mentioned that all the validation and calibration areas are located in the central part of the Gard region and have a similar moderate topography. It is probable that the rating method can not be extrapolated without further adjustments to the western part of the region which is mountainous and where the density of PICH points is much lower (see Fig. 1). Nevertheless, the same trends as observed in the central part of the region seem to be observed its western part: PICH points have a tendency to be concentrated in the valleys of the main rivers, downstream, where the valleys become larger.

The information about the flooding frequencies contained in the PICH inventory offers another validation opportunity for the selected susceptibility rating method. Figure 7 shows the cumulative distributions of the return period of submersion for the PICH points of the first 3 susceptibility classes. Again, the sorting out based on the selected indicators is far from perfect. But the susceptibility ranking based on these distributions is consistent with the defined classes. The highest susceptibility class contains a very large majority of frequently submerged points. Almost 80% of the PICH points of this class, have an empirical flooding return period smaller than one year. Likewise, almost all the PICH points with empirical flooding return periods higher than 10 years are part of susceptibility class 3.

This second validation result confirms the adequacy of the proposed susceptibility rating method. Even if the susceptibility to flooding is the result of a variable combination of factors, the major explanatory factors, at least in this part of the Gard region, seem to have been depicted. Note that classes based on the discharge ratios were far less consistent with the empirical flooding return periods, confirming what could be guessed based on the previously presented results: systematic under-sizing of the river crossing structures is not the dominant cause of road submersions in the Gard region. The most affected roads are generally located downstream large watersheds, in flat and low-elevation areas, typically in large floodplains. It is not necessarily the river crossing structure which is submerged in such configurations but rather a point on the access road to this structure located in the flood plain (see Fig. 8).

6 Conclusions

The PICH inventory realized in parts of the Gard region in France gave a unique opportunity to analyse the causes of road submersions in an area frequently affected by flash floods and to develop a road submersion susceptibility rating method, first element of a road warning system.

According to the low correlation coefficients between the observed flooding frequencies and the tested possible explanatory factors (indicators) and to the structure of the data set, specific analyses methods, based on the general principals of the discriminant analysis, had to be adapted. From a methodological point of view, the obtained results illustrate that information can be extracted from a data set even in such an unfavourable case.

Despite the various sources of uncertainties and the variability of local situations, the analyses revealed some general trends:

1. The size of the river crossing structures is far from being the only factor affecting the susceptibility of roads to flooding.

2. Frequently submerged road sections have a general tendency to be located downstream large watersheds, in flat and low-elevation areas, typically in large floodplains.

3. Additional data (field surveys and technical reports) indicate that it is not necessarily the river crossing structure which is submerged but rather a point on the access road to this structure located in the flood plain.

Based on the analysis results, four susceptibility categories have been defined for the section points between roads and rivers. Validation tests have shown that this classification is robust, at least in the same geographical area. It appears also consistent with the observed submersion frequencies: the most frequently submerged points of the road network are effectively concentrated in the highest susceptibility classes.

Of course the proposed road susceptibility rating method has its limits: the rating is limited to the definition of four classes and the sorting out of the road points according to their susceptibility is not perfect. Despites these limits and beyond the few lessons drawn about road submersions, it can be of practical use. A companion paper (Versini et al., 2010) will present the coupling between a distributed rainfall-runoff model and this susceptibility rating method to produce flooding risk maps. This work will show that susceptibility rating is essential to produce effective flood risk maps and especially to identify the points that are the most at risk in areas affected by intense rain. It highly contributes to the accuracy of the risk mapping when it is used to detect actually flooded roads.

To conclude, it is important to keep in mind that the obtained results are linked to the study area and to some methodological choices. The susceptibility of the roads to flooding may vary between regions with the local geomorphological patterns and the road construction habits. Moreover, the normalized indicator values and hence the defined thresholds are not independent on the extent of the considered areas and on the gradient of values within an area. The normalization method will certainly be put in question if the approach has to be extended. The presented work shows that it is feasible to define submersion susceptibility rates based on commonly available geographical data. But, the method should not be extrapolated to other regions without a further calibration and validation effort.

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