Geographical Information System for the assessment of vulnerability to urban surface runoff

Système d'Information géographique pour l'évaluation de la vulnérabilité au risque de ruissellement urbain

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ABSTRACT

The aim of this article is to develop and evaluate the methods for a surface runoff assessment and its potential consequences in an urban environment on the case of city Dijon (France). The applied methodology is based on identifying and quantifying stakes by means of geographical information system. Thanks to the multicriteria method (AHP) applied during the research, the weight of each exposed element could have been assessed. The investigation presented in this paper yielded in a spatialized global vulnerability index, while permitting an analytic query.

RESUME

Cette étude a pour objectif de contribuer au développement de méthodes d'analyse de la vulnérabilité des territoires urbains face à un épisode de ruissellement pluvial urbain. La méthodologie appliquée à l'agglomération dijonnaise consiste à identifier et à quantifier les enjeux à l'aide d'un système d'information géographique. Le poids de chaque élément exposé dans la vulnérabilité globale a été estimé grâce à la méthode hiérarchique multicritère (MHM). Le résultat se présente sous forme d'un indice de vulnérabilité spatialisé et synthétique, mais laissant la possibilité d'effectuer une interrogation analytique.

KEY WORDS

Geographical information system, multicriteria decision approach, spatio-temporal database, urban surface runoff, vulnerability.

1 INTRODUCTION : CONCEPTS OF VULNERABILITY IN URBAN SURFACE RUNOFF RISK ANALYSIS

Urban floods which resulted from an urban surface runoff are characterised by an extremely rapid kinetics. This kind of floods is dangerous because of its extent as well as its suddenness. This risk, which is closely linked with the phenomena of the soil impermeability, concerns not only the regions where the hydro-climatic conditions favour this kind of hydrological response (Mediterranean), but generally the areas affected by extension and densification of build up areas.

To study the functioning of urban catchments in the condition of rapid floods, the urban hydrology uses several tools based on hydrological modelling. Nevertheless, in the field of assessment of the consequences of surface runoff events, the concepts are still not very formalized, with a little number of case studies. In this context our research is keeping with the global approach of vulnerability which permits to apprehend the vulnerability in its totality and to take into account its qualitative aspects (d'Ercole 1994).

The application of global vulnerability analysis requires the integration of numerous information regarding human, environmental and material stakes. After the exposed elements inventory, the next step is to determine the vulnerability factors for each of them. Then, these factors should be merged in order to constitute an integral zoning which would express the global vulnerability of an area. In this last step, the main difficulty occurs in mapping this synthetic spatial information without loosing sight of the relations between vulnerability components (Propeck-Zimmermann 2003).

The analysis of vulnerability to surface runoff applied on Dijon agglomeration (France) was carried in order to produce a global vulnerability index using an analytic hierarchy process (Saaty 1980). The use of a geographical information system (GIS) allows us to specialize exposed elements and to reach a global mapping while permitting an analytic query (about human, environmental or material vulnerability).

2 APPLICATION OF THE ANALYTIC HIERARCHY PROCESS FOR THE VULNERABILITY STUDY

2.1 Multicriteria decision approach in vulnerability analysis

Multicriteria decision approaches are usually used in the field of the enterprise or project management, when one or many decision-makers have to make a choice or assess problems in complex situations. The aim of this study is not to find one or many solutions but to manage into hierarchy different targets according to their degree of vulnerability to the urban surface run-off in order to build a global vulnerability index.The multicriteria methods have already been used many times to assess the vulnerability of an area. Concerning the risk of floods, multcriteria methods have been used to compare the vulnerability of different sites according to socio-economical, hydrological and the rescue organisation criteria (Graillot *et al*. 2000). The same methods have been used to assess the vulnerability of an area to the risk of dangerous goods transportation in order to help the decision-makers in rescue planning. Recently, in the frame of the european project ARAMIS, analytic hierarchy process (AHP) was applied to assess the vulnerability of an area surrounding an industrial site.This paper inspired by the ARAMIS project, propose an application of the multicriteria method merged with spatial analysis to obtain a semi-quantitative vulnerability assessment of a city to the urban runoff risk using geographical information system.

The method chosen for the research is the analytical hierarchy process invented by T. Saaty (Saaty 1980). This method proposes a data organisation model easy to comprehend. It reflects the natural way of thinking by sorting the elements of a system in different classes and by grouping similar elements on a same level to solve non structured problems. Moreover, the AHP gives a flexible method which allows us to establish priorities and to restore them on different levels of hierarchy. It also allows us to evaluate the coherence of judgements used to determine priorities. This method also permits the selection of the best solution in accordance to purposes found by developing a compromise between several judgements expressed by experts.

2.2 Development of hierarchical tree and priorities calculation

The first step of the AHP is a construction of a describing the studying system. The hierarchy created in this way, largely inspired by the one established in the frame of ARAMIS project, gives us a structured view of the problem in terms of goals, criteria, sub-criteria and alternatives.

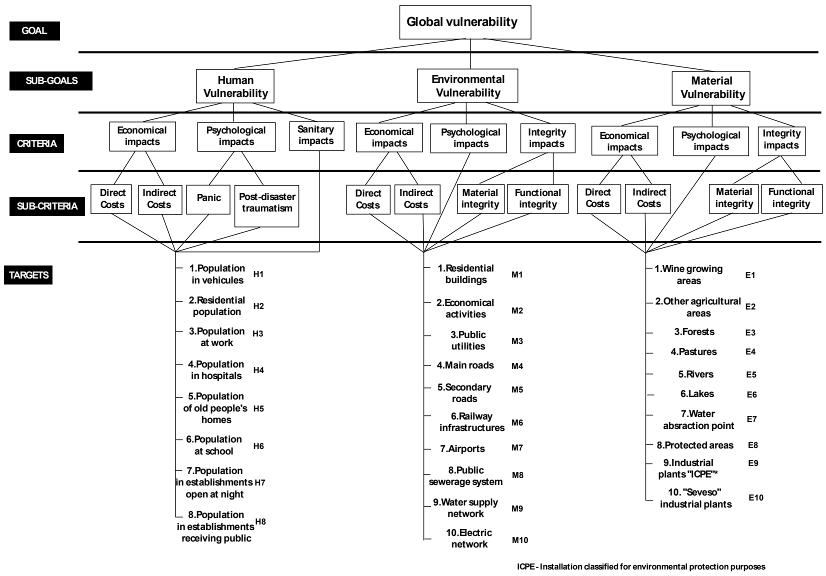

Figure 1: Vulnerability hierarchical tree

The assessment of global vulnerability includes the evaluation of the vulnerability of human, environmental and material targets. Vulnerability of each of these elements is a function of surface runoff impacts on them.

Three categories of the impacts were consider as criteria, and were divided into sub-criteria. Sanitary or integrity impacts which qualify the surface runoff effects on human, environmental or materials targets. For environmental and materials targets the integrity impact was divided in respect for the way that surface run-off affect the physical or functional integrity (capacity of the target to ensure his function after being impacted). Economical impacts which qualify surface runoff effects on targets in terms of costs, both: direct (cost connected to the destruction of the target) and indirect (cost of rehabilitation, exploitation loss, technical unemployment…). Psychological impacts which qualify an influence of surface runoff event on a group of people. For human targets two types of psychological effects were identified: the panic and the post-disaster traumatism. The lowest level of the hierarchy is composed of alternatives: human, environmental and material targets.

The hierarchy proposed in this paper should not be consider as final, and will be enriched by introducing other criteria related with rescue organisation and area susceptibility to surface runoff (such as runoff coefficient, slope etc.)

The second step of the method was to evaluate the priorities based on expert judgements. Those judgements, proceeded by the authors, were based on the knowledge of the flood impacts collected principally in the work of Gilles Hubert and Bruno Leroux concerning the costs of the risk (Hubert, Ledoux 2003). In the future, the judgements will be done by decision-makers and local experts from the field of risk management (DDE (Equipments Agency), DIREN (Environment Survey), municipalities).

Finally, the coherence of the judgements was evaluated in order to validate obtained priorities, otherwise to revise our appreciations.

3 DATA MODEL AND INTEGRATION OF THE INFORMATION INTO A GIS

3.1 Structuring the data by using a conceptual model

The data, necessary for accomplishing this study was obtained from a different services of "Grand Dijon" agglomeration and from decentralized state services (DRIRE (Industry Research and Environment Survey) DIREN, civil safety, Education Offices) as well as some commercial databases of INSEE (National Institute of Statistics and Economical Research), IGN (National Institute of Geography), DGI (General Taxes Agency). Data sources are presented in details in the figure 2.

Human targets	Residential population	Population at work	Population in vehicles	Population in hospitals	Population of establishments open at night	Population at school	Population of old people's homes	Population of establishments receiving pulbic		
Data sources	DB ILÔT (INSEE), DGI	DB SIREN (INSEE)	hightways departement Dijon	Prefecture	Prefecture	Education offices	Prefecture	Prefecture		
Environmental targets	**Pasture**	**Forest**	**Agricultural areas**	**Wine-growing areas**	**Lakes**	**Waterways**	**Espaces protégés**	**Industrial plants ICPE**	**Industrial plants Seveso**	**Points de captage**
Sources	Satellite image ERS	Satellite image ERS	Satellite image ERS	Satellite image ERS	Cadastre	Cadastre	DIREN	DRIRE	DRIRE	DB CARTHAGE
Material targets	**Residential buildings**	**Economical activities**	**Public utilities**	**Airport**	**Railway infrastructures**	**Main roads**	**Secondary roads**	**Public sewerage System**	**Water supply network**	**Electric network**
Sources	Buildings layer (Grand Dijon) DGI	Buildings layer (Grand Dijon) SIRENE	Buildings layer (Grand Dijon) SIRENE	Cadastre	Cadastre, DB Route 500 (IGN)	Cadastre, DB Route 500 (IGN)	Cadastre, DB Route 500 (IGN)	Grand Dijon	Grand Dijon	DB Route 500 (IGN)

Figure 2: Data sources.

This heterogeneous data were afterwards structured into a conceptual data model in order to represent the reality under study. It proposes a precise description of features chosen for the study, their attributes and relations between them. The objective is to integrate the information related to an area and to his functions in order to extract vulnerable stakes and to produce a global vulnerability index.

The model (fig.3) was divided on two sub-sets:

- A sub-set *area* which group the information concerning the area as its material components (parcels, buildings, addresses, roads, urban networks) and functional components (activities, populations and their displacements).
- A sub-set *stakes* which describes human, environmental and material elements susceptible to be impacted by a hazard. This sub-set is linked with sub-set *area* trough the parcel and the urban network classes.

The identification of the stakes allows us to evaluate different types of vulnerability in order to obtain a global vulnerability index based on priorities deduced from AHP and stakes quantification factors. These factors will be discussed in following part of the paper.

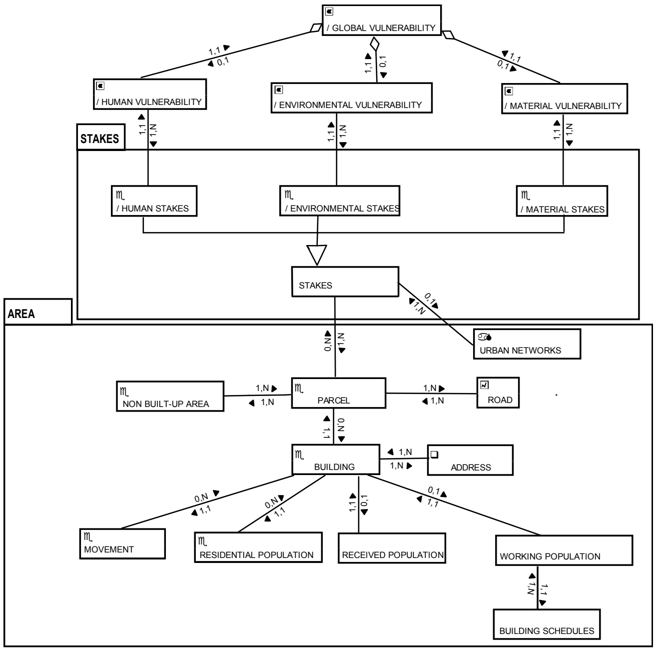

Figure 3: Simplified conceptual data model

3.2 Quantification of targets

3.2.1 Integration and quantification of human targets

The human targets were treated in a particular way allowing consideration of the variations of their repartition during a typical day. The method we propose consists of four main steps.

Potentials of emission and reception were evaluated for every building located in the area under study. Three types of potentials were determined for every building: a residential potential, a potential of employment and a potential of public reception. These potentials will be used to allocate movements in buildings.

The residential potential was calculated from the population (Pi) of “îlots” (basic statistic division of French census), the number of housings in “îlots”(Li), the number of housings in parcels, the surface of buildings (Sb) and the surface of residential build-up area in parcels, according to the following expression :

$$\Pr = \frac{(Sb \div Sp) \times Lp}{Li} \times Pi \quad (1)$$

The potential of employment was calculated from the number of employees in parcels (Ep) obtained from the SIREN database, the surface of buildings (Sb) and the surface of build-up area identified as economic activities or public utilities in parcels (Sp), according to the following expression: $Pe = (Sb \div Sp) \times Ep$ (2)

The potential of public reception corresponds to the capacity of the establishments receiving public.

The schedule of economic activities of the city was determined from the results of a survey carried by the “Grand Dijon” concerning 500 activities. The most frequent schedule was allocated to the activities of the same type according to the NAF60 nomenclature. A sample was realized for the public utilities and allocated to the other activities by using the same method. At last, the schedules of school buildings are exhaustively known. For every building, schedules are coded in half-hour periods for every potential according to a binary code (1: opened, 0: closed).

The treatments of the mobility survey concern 1400 people polled Tuesday and Thursday in order to obtain the movements during a typical day; after the redress some 700 000 movements are obtained. For every motif of movement considered in the survey and for every sector of the survey division, matrixes are built to obtain a balance matrix which corresponds to the difference between the emitted and received movements by sectors in half-hour periods.

At last, the allocation of matrix of balance in buildings was realized proportionately to the open buildings potentials in every period and every sector of the survey. The matrix of balance concerning the residential motif was allocated according to the residential potential. The matrix concerning the work was distributed in accordance with the potential of employment and the other matrixes according to the potential of public reception.

At the end of these treatments, we obtain an estimation of the number of people in buildings at different periods of a typical day. These values were normalized for every target identified from the function of buildings to obtain a factor which allows to quantify targets in 50 meters meshes covering all the area under study.

For the target H1, the quantification factor is as follow:

$H = T/T_{max}$ (3), where T- traffic of the road crossing the mesh and T_{max}- maximal observed traffic on a road of the area under study.

For the others, the quantification factor is as follow:

$H = N/N_{max}$ (4), where N- number of people in the mesh and N_{max} - maximal number of people from considered target in a mesh of the area under study.

3.2.2 Quantification of material and environmental targets

The quantification factors of the material targets are the following:

For targets M4, M5, M6 and M7: $M = S/S_{max}$ (5), where S- surface of the target in the mesh and S_{max}- maximal surface of the target in a mesh of the area under study.

For targets M8 and M9 and M10: $M = L/L_{max}$ (6), where L- length of the target in the mesh and L_{max}- maximal length of the target in a mesh of the area under study.

For targets M2 and M3: $M= E/E_{max}$ (7), where E- number of employees in the mesh and E_{max}- maximal number of employees in a mesh of the area under study.

For targets M1: $M= Lo/Lo_{max}$ (8), where Lo- number of housings in the mesh and Lo_{max}- maximal number of housings in a mesh of the area under study.

The quantification factors of the environmental targets are the following:

For targets E7: $E= P/P_{max}$ (9), where P- withdrawal from the water abstraction point located in the mesh and P_{max}- maximal withdrawal observed for a water abstraction point of the area under study.

For the others: $E= S/S_{max}$ (10), where S- surface of the target in the mesh and S_{max}- maximal surface of the target in a mesh of the area under study.

4 FIRST RESULTS

4.1 Results of Analytic Hierarchy Process

To assess the vulnerability functions and factors the eigenvectors of the judgements matrixes was calculated. The solution corresponds to the factors of vulnerability multiplied by quantification factors. To evaluate the coherence of judgements the ratio of coherence was calculated. For all 40 questionnaires the ratios of coherence was lower than 10%, so the vulnerability factors are validated. The global vulnerability function presented by equation (11) shows the great importance of human vulnerability which represents 81.3% of global vulnerability. The environmental vulnerability factor represents 14.3%, while the material vulnerability factor: 4.4%.

$$V_{global} = 0.8134 \times V_{human} + 0.1428 \times V_{enviro} + 0.0438 \times V_{material} \quad (11)$$

We can also restore the results of AHP for three types of vulnerability under study by analysing the weight of every sort of impact on targets. Functions (12), (13) and (14) show that for every kind of target the integrity impact was dominating (between 73% and 58%). For environmental and material vulnerability the economical impact was largely more important than the psychological one (28% and 34% against 10% and 6%), while for human vulnerability the psychological impact was more important (18% against 8%).

$$V_{human} = 0.73108 \times I_{integrity} + 0.186935 \times I_{psychological} + 0.081985 \times I_{economical} \quad (12)$$

$$V_{enviro} = 0.609265 \times I_{integrity} + 0.10709 \times I_{psychological} + 0.283645 \times I_{economical} \quad (13)$$

$$V_{material} = 0.58212 \times I_{integrity} + 0.0695 \times I_{psychological} + 0.34838 \times I_{economical} \quad (14)$$

Finally, equation (15) shows an example of how the vulnerability function was calculated for every target.

$$(V_{human})I_{psycho} = 0.56942352 \times H1 + 0.01203693 \times H2 + 0.01726024 \times H3 + 0.09079795 \times H4 + 0.05044577 \times H5 + 0.14156889 \times H6 + 0.08030606 \times H7 + 0.03816065 \times H8 \quad (15)$$

Each function was calculated for every mesh in order to map the vulnerability indexes.

4.2 Global vulnerability index mapping

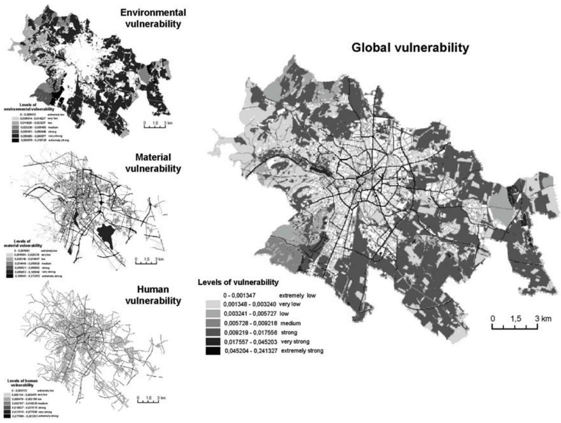

Figure 4: Global vulnerability mapping at 7 pm

At the end of our treatments it is possible to restore results in many different sets of vulnerability maps: the vulnerability map for each type of target and for different moments of a day, the global vulnerability map also for different moments of a day. The little size of this paper allows us to show just an example of vulnerability mapping.

5 CONCLUSIONS AND PERSPECTIVES

The methodology applied take into account the environmental, material and human vulnerability in order to build the global vulnerability index. In this way three categories of targets were quantified into a GIS and weighted according to judgements of their priorities in order to obtain vulnerability functions. The integration of the index into a GIS gives a tool easy to operate which allows to proceed analytical queries. Afterwards, the methodology proposed will be improved by integration of experts' judgements to determinate priorities. The hierarchical three will be enriched with elements designing the susceptibility of the area to increase a surface runoff event (slop, runoff coefficient etc.) and the efficiency of rescue organisation (accessibility etc.). It would also be interesting to take into account the perception of the risk and risk culture of local population. Finally, the modalities of normalization applied for targets quantification should be revised. Indeed, the applied normalisation function increase the values of spatial features, values, while it squeezes the population data (the environmental and material vulnerability appear more important than the human one). In conclusion, even than the numerous improvements are necessary, the proposed methodology shows an interest because of its flexibility and evaluative character.

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