Urban flood risk assessment using sewer flooding databases
Nicolas Caradot, Damien Granger, Jean Chapgier, Frédéric Cherqui and Bernard Chocat

ABSTRACT
Sustainable water management is a global challenge for the 21st century. One key aspect remains protection against urban flooding. The main objective is to ensure or maintain an adequate level of service for all inhabitants. However, level of service is still difficult to assess and the high-risk locations difficult to identify. In this article, we propose a methodology, which (i) allows water managers to measure the service provided by the urban drainage system with regard to protection against urban flooding; and (ii) helps stakeholders to determine effective strategies for improving the service provided. One key aspect of this work is to use a database of sewer flood event records to assess flood risk. Our methodology helps urban water managers to assess the risk of sewer flooding; this approach does not seek to predict flooding but rather to inform decision makers on the current level of risk and on actions which need to be taken to reduce the risk. This work is based on a comprehensive definition of risk, including territorial vulnerability and perceptions of urban water stakeholders. This paper presents the results and the methodological contributions from implementing the methodology on two case studies: the cities of Lyon and Mulhouse.

Key words | hazard, intensity, quality of service, risk analysis, road water levels, sewer flooding database, urban flooding

INTRODUCTION
Protection against urban floods caused by sewer spills (sewer flooding) is one of the functions traditionally assessed in the management of the urban drainage system. The level of protection is often based on the simulation of system behavior for specific rainfall return periods. This method is widely used in the design phase in order to determine the dimensions of each part. For the management of an existing system, simulations may also be used to determine sewer flooding characteristics, if the model is correctly calibrated. However, simulating sewer flooding remains very complex, due to the numerous possible causes (blockages, hydraulic overloading, line break, etc.), the difficulty in predicting significant factors (causes of blockages), and the various flooding locations in the system (manholes, retention tanks, etc.). In order to compensate for these issues, other data related to the behavior of the system can be used (mainly observed flooding, complaints from inhabitants, operational problems, etc.). Few studies have been done using flooding databases and causal analysis in order to improve urban drainage management (ten Veldhuis et al. 2009).

The main objective for water managers is to ensure or maintain an adequate level of service, that is to say, ‘service-ability’ (Arthur et al. 2009b). Serviceability requires taking into consideration not only the characteristics of flood events (hazard probability and intensity) but also their consequences on the urban receiving environment (vulnerability, elements at risk).

This paper aims to propose and apply a methodology in order to (i) help utility managers to assess the level of service related to urban flood protection at city scale and (ii) identify the means for improving it when necessary. One key aspect of this work is to provide risk analysis using a sewer flooding database. Utility managers often possess a sewer flooding database but this database is often underused. The approach proposed hereafter does not seek to predict flooding, but rather to inform decision makers about the current level of
risk and actions needed to reduce this risk. Two operational objectives have been identified:

- Firstly, the assessment should provide a flood risk map at city scale for managers and decision makers. The objective is to define a reproducible and flexible method for determining the risk of sewer flooding in every area of the city, which tells the manager (i) which areas are subject to a higher risk of flooding, and (ii) ranks the relative risk between these areas.
- Secondly, the assessment should determine causes of flooding in the areas most at risk. This step provides managers with the information necessary to manage flooding effectively and thereby to improve the quality of the service provided.

The strategic debate about improving the quality of service will be based on the definition of priority areas and actions upon those areas.

**RISK ANALYSIS**

Risk can be defined as the amount of loss, damage and nuisances expected for a given event (Varnes 1984). It encompasses a wide range of harmful effects on human health, goods, public infrastructure, ecological systems, industrial production, etc. (NRMMC 2004). *Elements at risk* are the units or systems which could potentially be affected by a specific event. They include populations, households, firms, economic production, buildings, public infrastructure, ecological species, landscapes, etc. The actual amount of flood damage for a specific flood event also depends on the *vulnerability* of the elements at risk, i.e. their potential to be harmed by a specific flood event. Thus, risk can be estimated for a specific event on the basis of three components: hazard, elements at risk and vulnerability. The analysis should therefore focus on the characteristics of risk components (Tira 1997; Glade 2003; Barroca et al. 2006). Risk $R$ can be written as:

$$ R = P \cdot I \cdot V \cdot E $$

- $P$ is the probability of occurrence of a potentially damaging event (hazard probability),
- $I$ is the intensity of the hazard event (hazard intensity),
- $V$ is the vulnerability of the elements or area to flooding impacts and
- $E$ is the elements at risk.

The product $I \cdot V \cdot E$ refers to failure consequences (Cançado et al. 2008; Arthur et al. 2009b; Renard & Chapon 2010; ten Veldhuis & Clemens 2010). Hauger et al. (2006) highlighted the importance of these indicators called risk objects.

**Hazard probability ($P$)**

Hazard refers to the likelihood of sewer flooding during a specific period of time and in a given geographic area. Arthur et al. (2009a) have shown that in the UK, the majority of sewerage flooding incidents are not due to hydraulic overloading but to blockages. According to ten Veldhuis et al. (2009), ‘degraded urban drainage system conditions make a much larger contribution to the probability of urban flooding than the occurrence of heavy storm events’.

A water utility sewer flooding database helps identify the historic frequency of operational problems such as pipe blockages, gully pot obstruction, pipe breaks, etc. If the amount (observation years) and reliability of data is sufficient, the analysis of historical events can be used in order to identify operational problems and flooding locations. Due to the variability of causes of flooding and the variability of rain events, this approach cannot accurately predict all future sewer flooding. However, this approach at least provides the water manager with practical information on sewer system dysfunctions; information which models struggle to provide.

**Hazard intensity ($I$)**

Water level is the main characteristic used to estimate flood damage intensity (Degiorgis 2006; Hauger et al. 2006). It is known that other variables, such as velocity, turbulence, flood duration or toxic load can have a significant impact on the damage caused. However, these variables are very difficult to measure or estimate. They are usually assumed to be strongly correlated with inundation depth and thus ignored in the analysis (Messer & Meyer 2005) or included as secondary parameters (Penning-Rossell et al. 2005).

Considering water level as the unique determining factor to define hazard intensity, each sewer flooding recorded in the database can be assigned an intensity rate $I$ depending on the depth of flooding. A consultation was organized with 10 stakeholders from the Mulhouse agglomeration representing the fire department (1 stakeholder), urban drainage (1 stakeholder from the private sector and 1 stakeholder from the city), inhabitants (1 elected representative for the city, 1 elected representative for the county, 4 inhabitant representatives), the city’s urban planning department (1 stakeholder). The stakeholders were asked to work out several intensity rates depending on the height of flooding. According to their perception of risk, damage does not
increase in proportion to flooding depth. The water level threshold values were obtained from the survey (Table 1).

These values can qualitatively describe hazard intensity:

- A water depth of $<5\, \text{cm}$ defines the lower impact level: roads are passable, water usually stays on the road below the level of doors and would remain below electrical sockets and most of the furniture, even where it reaches interiors. Nevertheless even low water level could cause damage to carpet, wooden floors, etc.
- A water depth between 5 and 30 cm may have serious impacts: roads are hardly passable; water gets into houses and shops, reaching the level of electrical sockets and furniture.
- A water depth of more than 30 cm make roads impassable and causes serious damage to the interior of dwellings; some stakeholders consider this a drowning risk for a child or a young person.

Vulnerability ($V$)

According to Thouret & D’Ercole (1996), vulnerability can be described as the propensity – of a person, property, territory – to be damaged in the event of flooding. Vulnerability is always defined in relation to elements at risk and allows them to be ranked according to the severity of the damage they may suffer. Many authors have discussed the concept of vulnerability (Penning-Rowsell et al. 2005; Messner & Meyer 2005; Degiorgis 2006). It can be described by analyzing how sensitively an element at risk behaves when confronted with a hazard event.

Vulnerability is primary in determining the consequences and seriousness of the impacts. Therefore, we met with 10 stakeholders (presented in the previous section) in order to establish a local hierarchy of territorial vulnerability. An overall vulnerability rate is assigned to each kind of land use, depending on the seriousness of damage and nuisances (functional, economic impacts, etc.). This approach has already been developed and specifically applied to landslide risk analysis (Wong et al. 1997 quoted by Glade 2003). The vulnerability ranking has been calculated using the ‘card game’ method (Pomerol & Barba-Romero 2000): each card represents a kind of land use (13 land uses have been defined) and each stakeholder positions them according to their relative vulnerability: a score of one point is given to the least vulnerable area, and the score increases by one point per rank. The stakeholder can use a blank card to describe a large difference in vulnerability between two land uses. There is no limit for the number of blank cards. For example (Table 2), there are four blank cards between ‘highway’ and ‘housing’. During the meeting the responses of all stakeholders were presented and they were asked to come (if possible) to a consensus (Table 2). This method has previously been successfully applied to sanitation (Moura et al. 2011; Renard & Chapon 2010).

Each rate expresses the average vulnerability of an area affected by sewer flooding. Although the categories of flood location are not the same, these results are similar to those obtained by Arthur et al. (2009b).

Elements at risk ($E$)

Elements at risk refer to any unit and system which could potentially be affected by flooding in a certain area: the local or national economy, the natural environment, etc. The term also refers to people living, working or transiting through the area affected by flooding. The elements at risk rate completes and refines the vulnerability rate providing local information on the value and amount of elements affected by flooding.

The identification and quantification of the elements at risk is particularly difficult due to the different kinds of

Table 1 | Hazard intensity $I$ related to water level obtained from a consultation of 10 local stakeholders for the Mulhouse agglomeration (Granger 2009)

<table>
<thead>
<tr>
<th>Water level</th>
<th>Hazard intensity $I$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$&gt;30, \text{cm}$</td>
<td>10</td>
</tr>
<tr>
<td>5–30 cm</td>
<td>5</td>
</tr>
<tr>
<td>$&lt;5, \text{cm}$</td>
<td>1</td>
</tr>
</tbody>
</table>

Table 2 | Land uses and associated scores for vulnerability $V$ (Granger 2009)

<table>
<thead>
<tr>
<th>Flood location</th>
<th>Vulnerability score</th>
</tr>
</thead>
<tbody>
<tr>
<td>Health building</td>
<td>13</td>
</tr>
<tr>
<td>Public building</td>
<td>13</td>
</tr>
<tr>
<td>Commercial area</td>
<td>12</td>
</tr>
<tr>
<td>Industrial area</td>
<td>12</td>
</tr>
<tr>
<td>Housing</td>
<td>10</td>
</tr>
<tr>
<td>Highway</td>
<td>5</td>
</tr>
<tr>
<td>National road</td>
<td>5</td>
</tr>
<tr>
<td>Secondary road</td>
<td>4</td>
</tr>
<tr>
<td>Garage</td>
<td>3</td>
</tr>
<tr>
<td>Cellar</td>
<td>3</td>
</tr>
<tr>
<td>Parking</td>
<td>2</td>
</tr>
<tr>
<td>Pedestrian area</td>
<td>1</td>
</tr>
<tr>
<td>Park</td>
<td>1</td>
</tr>
</tbody>
</table>
impacts: functional, economic, environmental, etc. Elements at risk must therefore be defined with the local authorities considering the overall impact of flooding on each kind of land use.

Representing the risk score

The risk is calculated as mentioned in Equation (1). In order to visualize the areas most at risk, the risk density at city scale should be represented by adding up risk values in administrative (district, sector) or geometric (pixel, triangle, etc.) meshes. The case studies in the next section provide examples of risk maps.

Identifying the causes of failure

Once the risk is calculated and represented, the manager will have a picture of the quality of service provided at city scale. In order to improve the quality of service, the manager must: (i) identify the causes of flooding producing risk and (ii) know their quantitative contribution to the risk score.

Meetings with local experts, monitoring and database analysis help to build causality relations called ‘cause-effect’ relationships (Granger 2009) or fault trees (ten Veldhuis et al. 2009). These relationships linking risks and causes of risk show trends and do not purport to build an exhaustive model of the reality. They help to identify the main causes of flooding but cannot be used to forecast the behavior of the system in detail (for example the location of urban floods after reducing a major cause of flooding). Causality trees provide information on the causes of failures and thereby the actions to implement. This relevant information helps improve the quality of the decision-making process.

APPLICATION OF RISK ASSESSMENT TO TWO CASE STUDIES

The Lyon urban agglomeration, France

The ‘Grand Lyon’ includes 57 municipalities and covers an area of 515 km². The population is 1,300,000 inhabitants. The sewerage system is 2,700 km long and conveys sewage to eight wastewater treatment plants.

A risk score is calculated as mentioned in Equation (1), using only the P and V parameters, since no information on the intensity I was available. In this study, the elements at risk are not characterized to refine the vulnerability (E = 1). The hazard probability rate P is derived from the number of flood events during the last 10 years according to the data collected. Each flood event is weighted by the vulnerability rate V, according to the land use (Table 2). Each weighted flood is spatially added: the aim is not to forecast the location of urban flooding but to identify the areas with the most relevant urban flooding density (relevant in terms of number and consequences).

This database containing all sewer flooding has been developed since the beginning of the 1990s in order to improve sewerage management (more details may be found in Renard & Volte (2009) or Volte et al. (2007)). When a flood occurs, a standard form with details of the nuisance is filled in by an agent, recorded in the database and referenced in the GIS database (Geographic Information System). During the last ten years, the database has identified about 1,200 urban flooding events. Some of these floods have led to investigation and corrective actions: these data have been excluded from the database. The flood risk map concerns the remaining urban floods, that is to say 330 floods. The reliability of the database is unknown, however the water utility reckons that most sewer flooding is indexed and this constitutes the best available information on urban flooding.

The standard intervention form filled in by the agents contains the following fields (Figure 1):

- Date of the intervention, location (city, street and number).
- Nature of the area (highway, house, etc.).
- Type of sewer system (combined, sanitary or storm sewer) and nature of the outlet.
- Cause of the flooding (if known).
- Additional comments (water level, rain intensity and other details).

The risk density has been calculated at each point (pixel) of the city using a kernel density function:

\[ D = \frac{\sum_{i=1}^{n} R_i \cdot c_i}{S} \]  

where \( R_i \) corresponds to value of the risk score for sewer flooding \( i \) (derived from Equation (1)); \( c_i \) is a decreasing smoothing coefficient (Equation (3)) and \( S \) is the surface of a circle with radius \( R \) containing \( n \) sewer flooding.

\[ c_i = \begin{cases} 
1 - \left( \frac{r_i}{R} \right)^2 & \text{if } r_i < R \\
0 & \text{if } r_i > R 
\end{cases} \]

with \( r \) being distance between the pixel and the flooding \( i \).
Kernel density has been successfully used in other fields related to risk such as road accidents (Anderson 2009). According to the water utility's management needs, the risk density has been represented at two different scales:

- A strategic scale (Kernel density radius $R$ of 5 km). This representation gives a strategic overview on the areas most at risk at city scale (Figure 2).
- An operational scale (Kernel density radius $R$ of 1 km). This complementary representation shows the disparities

Figure 1 | Example of standard intervention form filled in by the agents.
within each area most at risk. It proposes an operational overview at the scale of the areas most at risk (Figure 3).

**Mulhouse urban agglomeration, France**

The Mulhouse urban agglomeration is managed by the company ‘Lyonnaise des Eaux’. It includes 16 municipalities and covers an area of 160 km². The population is 270,000 inhabitants. The sewerage system is 800 km long and conveys sewage runoff through the treatment plant in Sausheim. Since 1993, the private operator has developed a database containing all the sewer flooding treated by operational agents. A standard form with details of the nuisance is filled in and recorded in the database. It gives the date, the location of flooding (city, street and number), the nature of the area (highway, private road, etc.), the kind of sewer system (combined, sanitary or storm sewer), the severity of flood (water level, duration of flood, etc.), the cause of the flooding, the response-time between the observation and the intervention, the beginning and end of the intervention, the kind of operation performed and some comments if necessary. This form is similar to the form used in Lyon (Figure 1).
A risk flood map has been drawn up using urban flooding for the year 2008 and concerns 275 floods in the public domain (outside of buildings). The territory is divided into administrative areas: for each area, a risk score is calculated as mentioned in Equation (1). The hazard probability rate $P$ is derived from the number of floods occurring in the year. Each flood is weighted by the intensity rate $I$ (Table 1) and the vulnerability rate $V$ (Table 2). Elements at risk $E$ corresponds to the number of persons exposed to urban flooding: $E$ is derived from the density of population in each administrative area. Figure 4 presents the flood risk map obtained.

The map shows major risk density in the city centre of Mulhouse; 60% of interventions are concentrated in 8% of the territory. In this area, we compiled information about the causes of sewer flooding using the flooding database and local experts’ analysis. The fault tree obtained makes it possible to identify the major causes of urban flooding in the city centre:

- Gully pot blockage (dead leaves, soil): 37% of interventions.
- Blockage due to improper behavior of building constructors (concrete, rocks, sand): 27% of interventions.
- Blockage due to improper behavior of citizens (variety of solid waste): 27% of interventions.

At this stage of the methodology, the water utility may decide how to act. In this case study, operational measures were put into place in order to take direct action on the causes of sewer flooding. Firstly, links between sewage and
the road department have been established in order to collectively manage the cleaning of streets and sewage facilities; this action should lead to a reduction in gully pot blockages. Secondly, plans were made to distribute information booklets to construction trade and public works professionals in order to improve their behavior; this information booklet will explain the consequences of improper behavior for the city (urban flood) and for the professional responsible (financial penalty or obligation to repair the sewer link). In order to identify the professionals responsible, specific sewer inspections on construction sites are also under active consideration.

DISCUSSION

The methodology is applied to two territories of different sizes. The format, quality and amount of data from the two case studies also differ. The risk score contains uncertainties due to the reliability of the flooding database (missing data, difficulty for the technician to accurately complete some fields such as water level or cause of flooding). In both cases, sewer flooding data are not exhaustive but discussions with the water utilities (strategic and operational departments) highlight the representativeness of the collected data. Moreover, experts agree on the areas most at risk in both case studies. This approach can thus claim to represent or reproduce the perception of water utilities. Their visions are often empirical and flood risk maps may help to consolidate knowledge, to inform citizens, to justify public policy and improve communication between stakeholders.

In both cases, the assessment results must be refined by improving the quantitative and qualitative data. The analysis of the databases and their management reveals some areas for improvement:

- The redefinition of the most important fields to be filled in by the operational teams in the event of sewer flooding would help to more accurately qualify the risk variables.
- The clarification of the databases’ objectives in addition to the various operator services would encourage technical services and decision makers to take on board the methodology and improve data collection.
- The systematic implementation of all operational data within the GIS mapping tools would also facilitate data management and use.

Besides improving the data, the methods for calculating the risk variables have to be refined. The local hierarchy of territorial vulnerability must be tackled in more detail by meeting other experts and other local stakeholders. For the elements at risk, information from other urban services databases and institutions may be included; traffic, frequen-
tation of public spaces, etc. The improvement of methods to better characterize hazard, vulnerability and elements at risk would help to more accurately describe the reality of risk. However, it is important to notice that some parameters may have political consequences (for instance the choice of vulnerability scores) and local authorities must agree upon the choice of parameters.

Our approach aims to provide decision makers with clear and understandable information by means of a unique practical indicator: the risk of sewer flooding. The weight of each variable is thus crucial in the final representation of risk; each case study should define the relative contribution of each variable by appropriate sensitive analysis. The aggregation of risk factors also raises the issue of the compensation between the variables and thus the meaning of the final risk indicator. Our operational approach accepts this principle by assumption and for operational reasons, although further research should explore its limits. Nevertheless, a lower level of aggregation is matched with maps showing single risk factors such as sewer flooding occurrences or vulnerability to urban flooding. The combination of risk maps and factors maps provides stakeholders with a solid decision basis.

CONCLUSION

Sewer flooding databases are often available and provide relevant information for urban flooding risk assessment. Combined with other variables, they can help to identify the areas most at risk and enable the implementation of corrective actions in order to improve the quality of service provided. The definition of risk (i.e. the choice of risk factors) is a political decision and must be made in accordance with local authorities. Flood risk maps contribute to producing a common definition of the risk. Each risk map is specific to a territory and its stakeholders, encouraging dialogue and cooperation.

This study also confirms the impact of a degraded drainage system on flooding and more especially the predominant role of gully pot blockage (Arthur et al. 2009a; ten Veldhuis et al. 2009).

Flooding assessment improves the knowledge of managers and decision makers of one of the functions of the urban drainage system, as part of a more holistic assessment. Before implementing corrective actions, managers should
also consider the results of the assessment of other functions like the reduction of environmental impacts. Actions which aim to improve the quality of service provided for one function should not reduce the quality of service for the other functions (for example: implementing combined sewer overflow outfalls may reduce urban flooding but may also degrade the natural environment).

ACKNOWLEDGEMENT

The authors would like to express their thanks to ‘Grand Lyon’ and the ‘Lyonnaise des Eaux’ company, the water utilities for the cities of Lyon and Mulhouse. Our thanks also go to Florent Renard from ‘Université Lyon 3’, for his constructive comments. This research was funded by the French National Research Agency (ANR-09-VILL-004-01) under the framework of the OMEGA project and the OTHU (Field Observatory for Urban Water Management).

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First received 2 December 2010; accepted in revised form 18 March 2011.