Decision making in flood risk based storm sewer network design

Prise de décision pour le dimensionnement d'un réseau pluvial basé sur le risque d'inondation

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RÉSUMÉ
Il est largement reconnu que le risque d'inondation est à prendre en compte lors du dimensionnement d'un réseau d'assainissement pluvial. Le risque d'inondation est généralement une combinaison de la probabilité et des conséquences d'une inondation. Puisque le risque d'inondation ne correspond pas à une valeur fixe mais à une variable de probabilité, la comparaison entre le coût de construction et le risque d'inondation n'est pas directe. Cet article a pour objectif d'explorer la méthode de dimensionnement d'un réseau d'assainissement pluvial basée sur le risque d'inondation. Une optimisation multi-objectifs est proposée pour tracer le front de Pareto de dimensionnement optimal en terme de coût de construction et de risque d'inondation. Un processus de décision est ensuite appliqué afin de choisir le meilleur dimensionnement sur le front de Pareto. La méthode traditionnelle de dimensionnement d'un réseau d'assainissement pluvial, basée sur une pluie de projet prédéfinie, est utilisée comme l'un des processus de décision. Trois critères de décision basés sur le risque d'inondation, et communément utilisés, sont également examinés et appliqués dans cet article. 1) Le critère basé sur le risque d'inondation attendu, qui utilise la valeur attendue pour représenter le risque d'inondation ; 2) Le critère d'Hurwicz qui utilise deux valeurs statistiques tirées de la distribution de probabilité et leur donne un poids ; 3) Le critère de dominance stochastique qui évalue la dominance sur tout le domaine des valeurs possibles, ce qui en fait un critère strict qui toutefois ne parvient pas toujours à donner le meilleur choix. Selon les critères appliqués le choix aboutit à des décisions différentes. La procédure proposée est appliquée à un problème simple de dimensionnement d'un réseau d'assainissement pluvial afin de démontrer son efficacité et les différents critères sont comparés.

ABSTRACT
It is widely recognised that flood risk needs to be taken into account when designing a storm sewer network. Flood risk is generally a combination of flood consequences and flood probabilities. As flood risk is not a fixed value, but a probabilistic variable due to the stochastic driver-- storm, the comparison between construction cost and flood risk deduction is not straightforward. This paper aims to explore the decision making in flood risk based storm sewer network design. A multi-objective optimization is proposed to find the Pareto front of optimal designs in terms of low construction cost and low flood risk. The decision making process then follows this multi-objective optimization to choose a best design from the Pareto front. The traditional way of designing a storm sewer system based on a predefined design storm is used as one of the decision making criteria. Additionally, three commonly used flood risk based criteria are investigated and applied in this paper. The expected flood risk based criterion uses expected value to represent the flood risk. Hurwicz criterion makes use of two statistic values from probability distribution and weights them. Stochastic dominance based criterion exert dominance evaluation over the whole range of possible values, which makes it a strict criterion thus it sometimes fails to give the best choice. Different decisions are made according to different criteria as a result of different concerns represented by the criteria. The proposed procedure is applied to a simple storm sewer network design to demonstrate its effectiveness and the different criteria are compared.

KEYWORDS
Decision making; flood risk; multi-objective optimisation; storm sewer network design;

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1 INTRODUCTION

Storm sewer systems play an important role in urban areas. Without efficient drainage, storm water may cause frequent urban flooding which threatens properties, environment and public safety. Furthermore, sewer system is capital intensive. Therefore, when a storm sewer system is designed, an appropriate design level is very important as an under-designed level may bring unwelcome and unintended flood while an over-designed level results in a waste of public funds.

The traditional way to design storm sewer systems is based on a deterministic approach. A good performance is required under a predefined design storm. The design storm, either identified by experts or rule of thumb, is criticized to be subjective and may result in economical bias. It is now widely recognized that an adequate design level of a flood defense system is based on a good balance between the cost of protection and the possible future risk in the protected area (Vrijling 2003). For floodplain management, the economic framework of minimization of expected annual damages and flood management expenses, including structural and non-structural flood control options, is recommended (WRC 1983; Goodman 1984). Lund (2002) asserts that probabilistic benefit-cost analysis has largely replaced older forms of economic analysis performed by examining only a particular design flood.

Due to the stochastic property of storms, which are the main driver of drainage floods, flood risk is not a fixed value, but a probabilistic variable. Generally, flood risk is considered as a combination of flood consequences and probabilities. Thus the risk-based method to compare the construction cost and the flood risk reduction is not straightforward. This paper is mainly concerned with the decision making in storm sewer network design under the probabilistic flood risk. A literature review was undertaken on ranking scenarios under uncertainty in water management. A simple and frequently used method is to use a characteristic value, e.g. a mean value, a mean-plus-standard deviation value, etc, to represent the flood risk. Afterwards this fixed value becomes comparable with construction or maintenance costs. Moreover, Tung et al. (1993) proposed a project evaluation procedure based on the concept of stochastic dominance to evaluate the economic merit of water resources projects subject to uncertainty. However, these design criteria are usually used to help decision makers select the best management option among limited choices. Risk-based optimization problems have received less attention. This paper aims to explore the need to take flood risk into account when designing a storm sewer network. Due to the probabilistic character of flood risk, the decisions can not be exclusively made like with fixed values, but they highly depend on the attitude of decision makers towards risk. Typical examples of design criteria under risk consideration for the storm sewer network design are represented and applied. A multi-objective optimization process is conducted to compute the Pareto front trade-off between construction cost and flood consequence. The protection level is then chosen by decision makers according to their favoured decision criteria.

2 STORM SEWER NETWORK DESIGN

2.1 Problem definition

The sewer network design is a very comprehensive task, which covers many issues, e.g. network configuration design, pipe diameter and slope identification, detailed manhole structure design etc. In this paper, the search for optimal risk-based storm sewer network design is considered under the following assumptions:

(1) The network configuration (i.e. manhole positions, pipe layout and connectivity) is known;
(2) Both diameters and slopes of the pipes are decision variables;
(3) Flood consequence can be expressed with a monetary unit.

The objective of the risk-based storm sewer network optimization is to balance construction cost against flood risk reduction.

2.2 Construction cost and flood risk

For a given candidate storm sewer network, the construction cost can usually be expressed with an algebraic formula, while the flood risk is a probabilistic value due to the stochastic attribution of rainfall. These two values are added on an annual basis. This sum represents the total cost on the urban flooding area. Fig 1 gives a typical probability curve of the sum. The shaded part represents construction cost which is invariable, while the upper white part is the flood damage cost that may
change according to the extreme rainfall of a specific year.

Fig 1 Probabilistic total cost of a candidate sewer network

As a result, for each candidate sewer network, there is a probabilistic total cost curve representing its possible behaviour in the future. The ranking of the candidate networks requires comparisons between probabilistic values, which, however, are not as straightforward as comparisons between fixed values.

In this paper, the probabilistic curve of flood risk for a candidate network is obtained under design storms. The process is presented in Fig 2:

- Fig 2(a) shows the relationship between return period of rainfall events and their cumulative probabilities;
- Under each design storm, the flood depth is obtained using sewer network simulation model (Fig 2(b));
- The curve of Fig 2(c) gives the mapping relationship between flood depth and flood consequence;
- Integrating all information from (a), (b) and (c), the flood risk curve, giving the flood damage versus cumulative probability, is represented by Fig 2(d).

Fig 2 The procedure to define the flood risk curve

A design storm hydrograph can either be given directly or be created from IDF (intensity-duration-frequency) curves using the alternating block method (Chow et al. 1988).
In this paper, the flood depth is used to present the flood stage which determines the flood damage. Alternative options can be flood volume, flood water velocity, flood duration or a combination of two or more parameters. The performance of the storm sewer system is simulated by the SWMM software (Rossman 2008), which is well recognised for its modeling capacity. The surface flood is simply simulated by considering the surface area as ponds atop manholes. Flood depth on each street is evaluated as the maximum water depth from atop area. Generally the flood consequence evaluation requires taking into account all the relevant effects caused by the flood including tangible and intangible damages. In this work, only property damages are considered in order to simplify the problem; this does not affect the generality of the methodology.

2.3 Multiple-objective optimization

The sewer network optimization problem is concerned with two aspects: construction cost and possible flood consequence. A monotonic relationship between flood consequences and design storms for sewer networks is reasonably assumed, i.e. if the flood consequence of a sewer network under a design storm is larger than that of another network, flood consequences of that network under other design storms are always not less than those of the other network. A two-objective optimization procedure is proposed in this paper: one objective is to minimise the construction cost, the other objective is to minimise a characteristic value (the mean value is used in this paper) to represent flood risk. A Pareto front of optimal designs can be obtained at the end of this procedure. The Non-dominated Sorting GA-II (NSGAII) method (Deb et al. 2000) is employed as the optimizer.

3 DECISION MAKING METHODS

After obtaining a set of designs from the multiple objective optimization, each design can be described with a probabilistic curve representing its possible total annual cost as shown in Fig 1. A design criterion is needed to aid a decision maker to choose the best solution. Deterministic design based on a predefined design storm can be utilised in this process. Additionally, three frequently used criteria for decision making under uncertainty are given in the following.

3.1 The design storm based method

The criterion based on a predefined design storm is the traditional way to design a storm sewer network. This can usually be done through a deterministic approach. The construction cost is minimised and at the same time the design should guarantee no flood occur under the design storm. This criterion can be used to help decision maker select a best design after the Pareto front has been identified through multiple-objective optimization.

3.2 Flood risk-based methods

3.2.1 The criterion based on expected/mean flood risk

The expected value is widely used in decision making in risk-based water recourses management. It simply and reasonably uses an expected/mean value to represent the possible flood consequence. In addition to the previously mentioned studies, Korving et al. (2003), Morita (2008) and Ryu and Butler (2008) made their decisions on flood protection levels based on expected flood consequences.

In the sewer system optimization problem defined in section 2.1, the criterion based on the expected value is:

$$\min \ C_T = \int_0^1 (c_f(x) + c_c)dx$$  \hspace{1cm} (1)$$

where $C_T$ is the total cost, $c_f(x)$ is flood consequence, which changes with the cumulative probability $x$, and $c_c$ is the construction cost.

3.2.2 The criterion based on Hurwicz

Hurwicz criterion represents a range of attitudes from the most optimistic to the most pessimistic (Taha 2007). The criterion weights the lower and upper bounds of all candidate options by the respective weights $H_o$ and $(1-H_o)$ where $0 \leq H_o \leq 1$. For the sewer network design problem in this paper, the 5% and 95% percentile costs are used as the optimistic and pessimistic values, respectively. Therefore the objective of the problem is:
\[
\min \left( H_5 C_{95\%} + (1 - H_5) C_{5\%} \right)
\]

where \( C_{5\%} \) and \( C_{95\%} \) represent the total cost at 5% and 95% percentile. The value of \( H_5 \) reflects decision-makers preference towards optimism or pessimism. A preference rating of 0 indicates a complete pessimism.

### 3.2.3 The criteria based on stochastic dominance

The concept of stochastic dominance was initialised in the area of finance. Tung et al. (1993) firstly applied it to water resources projects evaluation. The first-degree stochastic dominance test (FSD) and second-degree stochastic dominance test (SSD) are generally used. For the problem defined in this paper, the preference of the decision maker increases as the total cost \( C_T \) decreases. The FSD checks if the value of the cumulative density function (CDF) of one candidate network is monotonically superior or equal to that of another. If it is, the former network is preferred. If the FSD test is indecisive, the SSD test, which is based on risk-averse decision-maker, can follow. Project \( a \) dominates projects \( b \) if for all the level of total cost \( C_T \):

\[
\delta F(b-a)(C_T) = \int_{C_T}^{\infty} [F_b(x) - F_a(x)] dx \geq 0
\]

where \( F^{(2)}_{b-a} \) represents the second-degree difference of cumulative probability between \( a \) and \( b \), \( F(x) \) is the cumulative probability at \( x \). Fig 3 shows that curve \( a \) dominates curve \( b \) according to FSD and SSD.

Fig 3 The stochastic dominance criterion according to a) FSD and b) SSD

However, with stochastic dominance, it can not always be concluded that one solution is better than the other. For example, in Fig3(b), if the intersect area \( n \) is larger than area \( m \), no favoured choice can be given between \( a \) and \( b \).

### 4 CASE STUDY

The outlined decision making process is applied to a storm sewer network design taken from Guo et al. (2007). The network has a simple layout (see Fig4). It consists of 29 circular pipes, 29 manholes and 1 outfall with a free outflow boundary condition. All pipes have the same Manning roughness coefficient of 0.013, with different lengths, being one of the lengths of 100, 200 and 300 meters. A subcatchment with area of \( 5 \times 10^3 \text{m}^2 \) contributes to each manhole. Each manhole is connected to a street with constant horizontal area of \( 100\text{m} \times 5\text{m} \). The surface flood is simply simulated by considering streets as areas atop the manholes. Flood depth on each street is abstracted as the maximum water depth from atop area.
The decision variables include pipe diameters of discrete values chosen from 0.15m to 1.20m with 0.075 or 0.15 increments and pipe slopes $S_i$ belong to a continuous interval $[0.0015, 0.05]$.

The optimization problem is constrained by two constraints: the cover over pipes should not be less than 0.5m and the excavation depth should not be more than 10m; pipe diameters at downstream should not be smaller than those of upstream pipes.

The construction cost of the sewer system mainly consists of: (1) Pipe cost; (2) Earthwork and (3) Manhole construction fees.

<table>
<thead>
<tr>
<th>Pipe diameter m</th>
<th>unit cost £/m</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.150</td>
<td>34</td>
</tr>
<tr>
<td>0.225</td>
<td>44</td>
</tr>
<tr>
<td>0.300</td>
<td>54</td>
</tr>
<tr>
<td>0.375</td>
<td>70</td>
</tr>
<tr>
<td>0.450</td>
<td>92</td>
</tr>
<tr>
<td>0.600</td>
<td>140</td>
</tr>
<tr>
<td>0.750</td>
<td>193</td>
</tr>
<tr>
<td>0.900</td>
<td>252</td>
</tr>
<tr>
<td>1.050</td>
<td>311</td>
</tr>
<tr>
<td>1.200</td>
<td>443</td>
</tr>
</tbody>
</table>

Table 1 Sewer pipe costs for Case Study

The cross shape of the trench is a trapezium: the width of trench bottom is $b=D_i+0.5$, the trench depth $d=D_i+D_c$, where $D_c$ is the depth of the pipe crown, and the angle of trench side wall with the vertical is $\theta=45^\circ$. The excavation volume $V$ is integrated along a pipe length. After simplifying the formula, it has the form as follows:

$$V = \frac{1}{3} \tan \theta S^2 L^3 + \frac{1}{2} (bS + 2d \tan \theta) L^2 + (bd + d^2 \tan \theta) L$$

(4).

where $d$ is the excavation height to the pipe crown upstream.

The manhole construction cost is assumed to follow the following function:

$$C(h) = 292.80h + 123.21$$

(5).

It is assumed that the storm sewer network is designed for 70 years use, the construction price is discounted for annual cost with the formula:

$$c_a = \frac{1 - \alpha}{1 - \alpha^n} c$$

(6).

where $c_a$ is the discounted annual construction cost, $c$ is the total construction cost and $\alpha$ is a discount
factor which can be calculated from $\alpha = 1/(1 + r)$, assuming the benchmark interest rate $r = 5\%$.

The IDF of design storms for this area is shown in Fig 5.

![Fig 5 The IDF of case study](image)

5 RESULTS AND DISCUSSIONS

5.1 Multiple-objective optimization result

The main schemes and parameters set in NSGAII are listed in Table 2.

<table>
<thead>
<tr>
<th>Population</th>
<th>Generations</th>
<th>Selection</th>
<th>Genetic operator</th>
<th>Crossover rate</th>
<th>Mutation rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>200</td>
<td>1000</td>
<td>Tournament selection (Number of parent chromosome=100; Tournament number=2)</td>
<td>Simulated binary crossover &amp; Polynomial mutation</td>
<td>0.9</td>
<td>0.1</td>
</tr>
</tbody>
</table>

The Pareto front of the two-objective optimization is illustrated in Fig 6. The flood risk is represented by the expected flood consequence value, which is a characteristic value actually representing a probabilistic flood risk cost. The construction cost starts from a threshold value, which is consistent with the existing minimum spending on the infrastructure due to the constraints of the problem. At the beginning, the increase in the construction cost is very efficient at reducing the expected flood risk cost. However, when it achieves certain level, where the capacity of the sewer network is adequate, further growth of the construction cost does not lead to significant reduction of the flood risk.

![Fig 6 The Pareto front of multiple-objective optimization of sewer network design](image)
The multiple-objective optimization provides a set of good designs by trading between construction cost and flood risk, however, further decision making method is needed to choose one best design.

5.2 Optimal designs by different criteria

The deterministic method based on a predefined storm and flood risk based methods listed in section 3 are used to help decision makers choose one design from the Pareto optimal front designs. For design storm based method, a return period of 10 years is assumed. The construction cost are minimised on the condition that no flood occurs under the design storm. For Hurwicz criterion, the identification of coefficient $H_\alpha$ is subjective according to the risk attitude of decision makers. It is assumed to be 0.5 in this paper. The best design chosen according to different design criteria and their main characters are listed in Table 3. The probabilistic total cost of each design, which gives the full information of a design, is represented in Fig 7 (the tails of the curves are magnified in the middle of the figure).

<table>
<thead>
<tr>
<th>Decision making methods</th>
<th>Chosen design</th>
<th>Construction cost (£)</th>
<th>Expected flood risk (£)</th>
<th>Return period</th>
</tr>
</thead>
<tbody>
<tr>
<td>Design storm based method</td>
<td>Best design</td>
<td>513562</td>
<td>12302</td>
<td>10</td>
</tr>
<tr>
<td>Flood risk based method</td>
<td>Expected cost based criterion</td>
<td>479376</td>
<td>34578</td>
<td>2</td>
</tr>
<tr>
<td>Hurwicz criterion</td>
<td>No best design can be given</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Stochastic dominance criterion</td>
<td>No best design can be given</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 3 Decision made according to different criteria

In this case, the Hurwicz criterion (when parameter $H_\alpha = 0.5$) gives the most conservative design. The expected cost based criterion offers the cheapest design but with the highest flood risk. The traditional design storm method (if the return period is set to be 10 years) provides a design between the former designs in terms of risk. These conclusions may be different when these criteria are applied to other cases, especially when some parameters such as storm return period and $H_\alpha$ can be adjusted based on decision makers’ attitude towards risk. The stochastic dominance based criterion fails to give the best design, i.e. there is no design that dominates all others. This is because this criterion is actually very strict in the sense that a dominance test is conducted over the whole range of the possible values. In order to give an appropriate design, a further decision making criterion is needed.

The preference of designs of the Pareto front according to the two flood risk based criteria, i.e. expected flood risk based criterion and Hurwicz criterion are represented in Fig 8. As different characteristic values are used to represent the uncertain flood risk, the preferences of designs according to the two criteria are not identical.
5.3 Discussion

The design storm based method is the traditional way to design storm sewer systems. Much experience and knowledge can be referred to when this criterion is adopted in practice. However, as it can not take flood risk into account explicitly, flood risk-based methods are theoretically sounder. Both construction cost (usually a fixed value) and flood risk (a probabilistic value) are considered. Each candidate sewer network design can be fully described by a probabilistic total cost. The comparison among probabilistic variables is not straightforward. Due to the uncertain character of the total cost, no unified way of decision-making exists. The expected value method uses a single statistic, with the physical meaning of the expected/mean value describing the possible flood consequence. Hurwicz criterion makes use of two statistic values and weights them. The weights reflect the risk attitude of decision makers. The stochastic dominance method considers flood consequence over the whole range and adopts a risk-aversion attitude for further consideration if no conclusion can be drawn in the first stage. This is a strict criterion and as a result it sometimes may not be able to offer a decision. There is no agreement about which criterion is better than the other and there are more than three risk-based methods for decision making. The chosen criterion for use should depend on major concerns of the specific problems.

It is worth mentioning that once a decision making method is determined, the storm sewer network design can be formulated as a single-objective optimization, whereby the optimization objective is built based on the chosen decision making criterion. The single-objective optimization problem can be solved without assuming a monotonic relationship between flood consequences and design storms for sewer networks, unlike in multiple-objective optimization. In this paper, the multiple-objective optimization is applied for the purpose of using different decision making methods at the same time and comparing them.

6 CONCLUSIONS

An adequate design level for a flood defence system is based on a good balance between the cost of protection and the possible future risk in the protected area. The traditional way of designing a storm sewer network does not take flood risk into account explicitly. A comprehensive decision should be made by considering flood risk, which is a combination of flood consequence and flood probability. The presence of the stochastic attribution of flood consequence prevents the decision making on flood protection level of storm sewer network from being straightforward. This paper explored a decision making process for the storm sewer network design. A multi-objective optimization is proposed to find the Pareto front of optimal designs in terms of low construction cost and low flood risk. A decision making process then follows this multi-objective optimization in order to choose the best design from the Pareto front. The traditional way of designing a storm sewer network with a predefined design storm and three typical criteria based on flood risk consideration are given and compared. There is no uniform decision making scheme when risk is involved, as different attitudes may exist towards risk. The expected flood risk cost is commonly used to represent the flood risk due to its simple and reasonable rational. Hurwicz criterion makes use of two statistic values from a probability distribution and employs weights to reflect decision makers’ attitude towards risk. Stochastic dominance based criterion exerts dominance evaluation over the whole range of possible values. This makes it a strict
criterion, which sometimes fails to give a best choice. There are more than three risk based criteria to facilitate decision-making. The chosen criterion should be based on the major concerns of the problem. The procedure proposed in this paper, which includes a multi-objective optimization and a decision criterion, has been applied to a simple storm sewer network design to demonstrate its effectiveness. Using flood risk based methods, the design chosen according to different decision making criteria are different as a result of different aspects being regarded by different criteria. For instance, the expected flood risk based criterion corresponds to the mean flood consequence of the possible future occurrence, while the Hurwicz criterion represents a range of attitudes from the most optimistic to the most pessimistic.

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