Sensitivity based attribution of flood risk

Attribution du risque d'inondation basé sur la sensibilité

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RESUME

Cet article présente l'exploration de nouvelles méthodes d'attribution des risques d'inondation à l'aide d'un modèle intégré synthétique de réseaux de drainage en milieu urbain. La seule approche permettant de traiter le vaste nombre de variable d'un système urbain consiste en une simplification hiérarchique du système. L'attribution de risques est analysée à plusieurs niveaux pour identifier les composants responsables du risque d'inondation. L'attribution basée sur la sensibilité répartit le risque entre les variables influençant le risque total. Cette approche utilise des moyennes statistiques pour analyser les dégâts dus à une série d'événements, dégâts basés sur la modélisation hydraulique déterministe de l'inondation de rues. Deux exemples d'attribution de risques basés sur les indices de sensibilités sont présentés.

ABSTRACT

A synthetic integrated urban drainage system is used in this paper to explore alternative methods for flood risk attribution. The only feasible approach to tackling the problem of huge number of variables in urban systems is by hierarchical simplification of the system, with the attribution analysis being applied at several levels, to identify the system components responsible for flood risk. Sensitivity-based attribution apportions risk between the variables that influence the total risk. In this approach, statistical means are used to analyse damage from a series of events, based on deterministic hydraulic modelling of street flooding. Two examples of risk attribution based on sensitivity indices are shown.

KEYWORDS

Flood damage, integrated flood risk management, risk attribution, urban flooding

1 INTRODUCTION

Integrated Flood Risk Management (IFRM) explicitly recognises the interrelationships between all sources of flooding, risk management measures, their analysis, costs and effectiveness, within changing social, economic and environmental contexts. The main sources of flooding include pluvial runoff that leads to sewers backing up and high surface flows, fluvial flooding caused by high river flows, coastal storm surges and perhaps also groundwater floods. A given flood event could be caused by a single source, or several sources acting in combination. The UK's Department for Environment Food and Rural Affairs (DEFRA) has identified IFRM as a key strategic aim (DEFRA *et al*., 2005). Likewise, initiatives such as the Water Framework Directive, Integrated Coastal Zone Management and proposed EU Floods Directive are driving the need for 'joined-up' thinking across Europe.

In order to demonstrate the technical feasibility of IFRM a necessary methodological advancement is the development of core concepts for a framework for unified systems-based flood risk analysis. After this introduction, we shall present these concepts and present in greater detail a key aspect of these concepts: a methodology for attributing risk between flood sources, management infrastructure and stakeholders. Implementation of this approach on a synthetic system will be shown.

2 SYSTEMS-BASED RISK ANALYSIS

The core principles of an integrated systems-based flood risk analysis are now defined as (Hall *et al.,* 2006):

1) *Risk is a 'common currency'*. To enable inter-organisational 'communication' of flood risk information, the first step is that it is measured using a common metric. Risk estimates provide the common currency which can be used to compare risks from different sources on a common basis. In a situation where there are several organisations responsible for risk management we wish to be able to disaggregate the total risk and attribute it to different components in the system.
2) *Risk is a multi-dimensional measure* and should be a broad measure of all losses (and gains) including social, environmental and economic.
3) *Spatial and temporal profiles* of this multi-dimensional measure of risk need to be constructed to support long term planning.
4) *Attribution of risk*. The contribution towards risk from different flooding sources and components of flooding pathways, including infrastructure components, is critical information to support risk-based decision-making:
    a) *Risk ownership*. There are several organisations with a role in flood risk management. We wish to know, in broad terms, what proportion of the risk each is responsible for.
    b) *Estimation of capacity to reduce risk*. Ideally, risk should be owned by organisations with the greatest capacity to manage it. Capacity to reduce flood risk is related to the potential to change the characteristics of the flooding system.
    c) *Asset management*. An organisation with responsibility for management of flood defence or drainage infrastructure should rationally invest resources so that they maximise impact in terms of risk reduction. Within a specified set of system components it is therefore necessary to identify those components that contribute most to risk and compare potential measures to reduce risk with the cost of implementing those measures in order to develop an optimum intervention strategy. A secondary problem is to target monitoring strategies so that resources are invested in data acquisition that makes the greatest contribution to reducing uncertainty.

2.1 Formulation of the risk problem

Consider a system which is described by a vector of loading variables S and a vector of variables that describe the flood management infrastructure system R. We write all of the basic variables as $X = (S, R)$. The resistance variables R might include the height or other dimensions of dikes, the properties that determine dike failure or the dimensions of the sewer system. Their variation might be continuous (e.g. a height variable) or discrete (e.g. a 'blocked' or 'not blocked' descriptor of a pipe.

The variability in the loading and resistance is described by a joint probability distribution $\rho(X)$. We may often be able to assume that many of the variables in R are statistically independent and we will often assume that S and R are independent. There is a damage function $D(X)$ where the units of D are £ (British Pound) or some other suitable measure of impact. The risk r associated with the system is therefore

$$r = \int_0^\infty \rho(X)D(X)dx \qquad (1)$$

The risk integral can be further extended to address antecedent conditions either by including antecedent variables in the loading vector S, or, alternatively, by extending the analysis so that S is a function of time. At any point in time the damage is $D(X)$; the risk is the instantaneous expected value of this function. A further attraction of the approach is that it can deal with other variations in the system state variables with time, for example due to deterioration in the condition in the variables describing the system state or changes in the loading due to climate change or other environmental changes.

2.2 Standards based attribution

Consider an organisation with responsibility for urban drainage (hereafter a UDO), providing a specified level of service to discharge rainfall events up to return period T_s, although it is likely that through degradation *etc*. the system only conforms to $T_s' < T_s$. Therefore, after a rainfall event, $T > T_s'$, the sewer and drainage capacity (even assuming no blockages) will certainly be exceeded.

A flood model can be used to estimate the damage $D(T_s)$ and $D(T)$ (by definition $D(T_s') = 0$). Damage attributable to the UDO is $D(T_s)$-$D(T_s')$ and damage not attributable to the UDO is $D(T)$-$D(T_s)$. This can be extended to give the expected attributed damage over the distribution of rainfall L:

$$\text{Expected attributed damage for UDO} = \int_0^{l(T_s)} \rho(L)D(L)dl \qquad (2)$$

where $l(T_s)$ is the rainfall with return period T_s.

This may be extended further to consider the situation in which due to blockage or some other sewer failure the damage is not $D(T)$ but $D(T|F)$ where F indicates some failure event in the sewer system attributable to the UDO. The damage not attributable to the water service provider is still $D(T)$-$D(T_s)$, so the damage that is attributable to them is now $D(T|F)$-$D(T)$+$D(T_s)$. The expected attributed damage calculation now requires a probability distribution over the various possible blockage states F_j:

$$\text{Expected attributed damage} = \int_0^\infty \sum_{j=1}^{2^n} P(F_j)\rho(L)D(L \mid F_j)ds - \int_{l(T_s)}^\infty \rho(L)D(L)ds \qquad (3)$$

However, $P(F)$ is notoriously difficult to estimate for sewer systems and so application of Equation 3 is likely to be limited.

2.3 Sensitivity based attribution

An intuitive measure of influence or sensitivity is the extent to which variation in a factor of interest (or a set of factors) has on a system performance, in our case flood risk *r*. This is the classical sensitivity analysis problem to which there are a number of solutions. However, relating sensitivity analysis to risk attribution is, in general, not straightforward.

If each of the loading variables (e.g. fluvial flows, rainfall) were the unequivocally responsibility of a particular agent, then sensitivity analysis would provide a basis for definition of risk ownership. Risk ownership could be disaggregated on the basis of sensitivity to the relevant loading variable. However, rainfall runoff, for example, is dealt with in sewer and highway drainage systems as well as urban water courses. Hence it is necessary to consider the variables *R* that define system performance. Evidently, this is also necessary to make asset management prioritisation decisions.

Risks arise because of phenomena whose future state is not known with certainty. If the magnitude of a given load on a system was known with certainty then decision-making would be easy. We would take measures to reduce the predicted damage if it was economical to do so and otherwise we would not. In other words we would know future losses precisely and the notion of risk, which is associated with phenomena that are only predicable in probabilistic terms, would be redundant. Because, in fact, the future is uncertain we construct the concept of *risk* and design measures to reduce risk i.e. to reduce the expected damage due to some uncertain hazards.

Variance-based methods seek to attribute risk to system variables on the basis of the amount that those variables contribute to uncertainty and hence to risk.

Consider a model of the form $Y = g(X_1,\ldots, X_k)$. The sensitivity index I_i represents the fractional contribution of a given factor X_i to the variance in a given output *Y*. In order to calculate the sensitivity indices the total variance *V* in the model output *Y* is apportioned to all the input factors X_i as (Sobol, 1993):

$$V = \sum_i V_i + \sum_{i<j} V_{ij} + \sum_{i<j<l} V_{ijl} + \ldots + V_{12\ldots k} \tag{4}$$

where

$$V_i = V\left[E\left(Y \mid X_i = x_i^*\right)\right] \tag{5}$$

$$V_{ij} = V\left[E\left(Y \mid X_i = x_i^*, X_j = x_j^*\right)\right] - V_i - V_j \tag{6}$$

$V\left[E\left(Y \mid X_i = x_i^*\right)\right]$ is referred to as the Variance of the Conditional Expectation (VCE) and is the variance over all values of x_i^* in the expectation of *Y* given that X_i has a fixed value x_i^*. This is an intuitive measure of the sensitivity of *Y* to a factor X_i, as it measures the amount by which $E\left(Y \mid X_i = x_i^*\right)$ varies with the value of x_i^*, while all the effects of the X_j's, $j \neq i$, are averaged. The first order (or 'main effect') sensitivity index S_i for factor X_i is therefore defined as:

$$I_i = \frac{V_i}{V} \tag{7}$$

Also of interest is the influence of factor X_i when acting in combination with other factors. There are 2^k-1 of such interactions, so it is usually impractical to estimate the effect of all of them. A more practical approach is to estimate the *k* total sensitivity indices, I_{Ti}, where (Homma and Saltelli 1996):

$$I_{Ti} = 1 - \frac{V\left[E(Y \mid X_{\sim i} = x_{\sim i}^*\right]}{V(Y)} \tag{8}$$

where $X_{\sim i}$ denotes all of the factors other than X_i. The total sensitivity index therefore represents the average variance that would remain as long as X_i stays unknown. The total sensitivity indices provide an indicator of interactions within the model. For example, factors with small first order indices but high total sensitivity indices affect the model output Y mainly through interactions – the presence of such factors is indicative of redundancy in the model parameterisation.

In the case of flood risk analysis, the output quantity of interest is the damage D. The probability density function of the annual damage estimate, $f_D(d)$:

$$f_D(d) = \int I_d(D(X))D(X)\rho(X)dx \tag{9}$$

where $I_d(\bullet)$ is the indicator function. Recall that risk r is the mean of D i.e.

$$r = \int_0^{\infty} \rho(X)D(X)dx \tag{10}$$

The variance is

$$Var(d) = \int_0^{\infty} \rho(X)D(X-r)^2 dx \tag{11}$$

The variance-based sensitivity analysis described above is applied to this function.

3 IMPLEMENTATION

The risk attribution methodology is implemented in the first instance on a realistic (but not real) system shown in Figure . Upstream of the urban area is a rural catchment of 50km^2. Runoff from rural catchment is discharged into the river that is the recipient for runoff from urban area. The area of the urban catchment is 1.5km^2, with 4.6km of storm sewer pipes (minor drainage system, with three outlets to the river) and 3.3km of streets/roads with assumed wide trapezoidal cross-section (major drainage system, with one outlet – link 185-163). Interaction between minor and major system can take place through virual weirs that link manholes to surface network nodes.

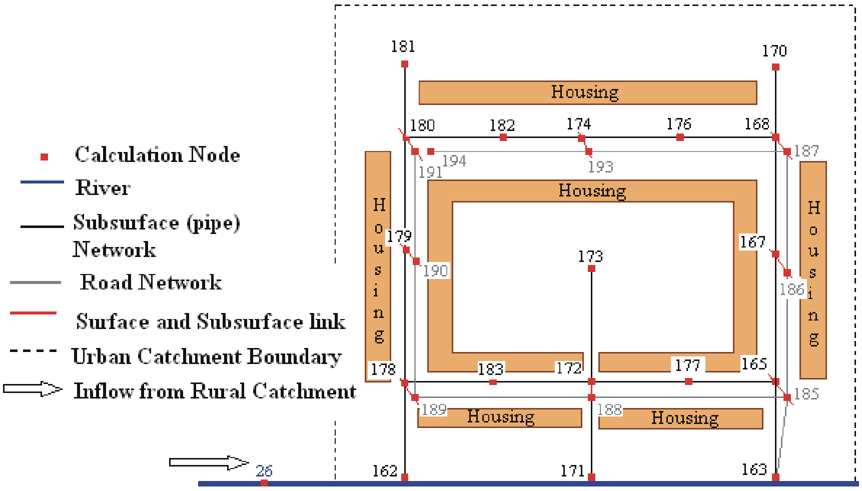

Figure 1 Urban flood system (catchment boundary covers area of 1.2km by 1.25km)

Pipes are “designed” so that, at low river flows (i.e. at free outflow from all outlets), sewer system can handle surface runoff from 1 in 10 year storms with surcharging but without the hydraulic head reaching the terrain level. At more intense storms, minor system capacity becomes insufficient and *pluvial* flooding takes place. On the other hand, assuming zero runoff from urban area, *fluvial* flooding occurs at river flows exceeding the 1 in 100 year flow rate. The urban area is susceptible to combined pluvial/fluvial flooding when backwater influence from the river may reduce the capacity of the sewer system. Properties (or damage points) are assumed to be spaced at 20m intervals along the roads.

Figure 2 shows steps required to generate estimates of flood risk, described below:

1) Rainfall boundary conditions are defined as a series of 50% summer profile storms (Butler and Davies, 2004) for return periods of 1 to 1000 years and durations between 15min and 24h.
2) The rainfall is propagated through a hydrological model ARNO (Todini, 1996) to give the upstream river flow rates for the hydrodynamic model.
3) The rainfall and river flow are used as inputs to the coupled surface/sub-surface hydrodynamic model, SIPSON (Djordjević *et al*., 2005).
4) Maximum flood depths obtained by the hydrodynamic model are integrated over functions describing depth-damage relationships for properties (Penning-Rowsell *et al*. 2003) to calculated the flood damage, *D*, for a given event.
5) The flood risk, expressed in terms of expected annual damage, is calculated using Equation (1).
6) The sensitivity-based analysis is subsequently applied using Equation (10).

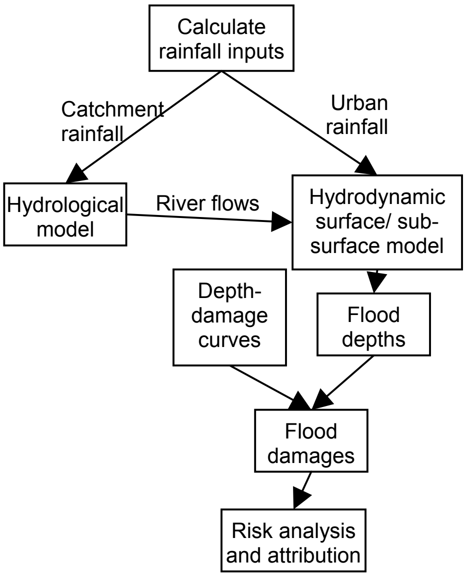

Figure 2 Model linkages for integrated flood risk assessment

In addition to varying loading parameters (rainfall duration, peak intensity and river flows), the following infrastructure parameters were varied:

1) Pipe size (uniform distribution, range -40% to +50% of the “designed” diameters).
2) Percentage of impermeable area (normal distribution, range 30% to 90%).
3) River bottom width (beta distribution, range 1.5m to 11m).

Based on sensitivity indices, the pie chart in Figure 3 shows the total contribution of each variable to risk. As is evident, duration, peak rainfall and pipe size are the most important loading variables. River width has no effect on flood risk and the influence of peak flow and impermeable area is generally insignificant. It should be noted that the obtained figures are very much case-specific and therefore should not be considered to have any general relevance. Instead, they should be taken as an illustration of the proposed methodology.

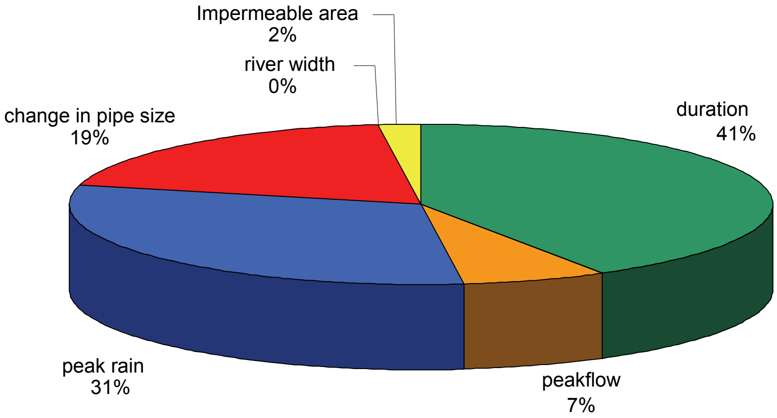

Figure 3 Total sensitivity indices

The influence of sewer blockages was analysed. Sensitivity indices were calculated for individual pipes (assuming their blockage) to identify which ones contribute most to the flood risk. As expected (see Figure 4), blockage of the lowest of the three outlets (pipe 165-163) contributes most to flood risk. Somewhat surprisingly, blockage of the middle outlet (pipe 172-171) would contribute insignificantly to flood risk. Other investigations made in this study included combinations of blocked pipes and analysis of the effect of climate change assuming different scenarios (Speight, 2006).

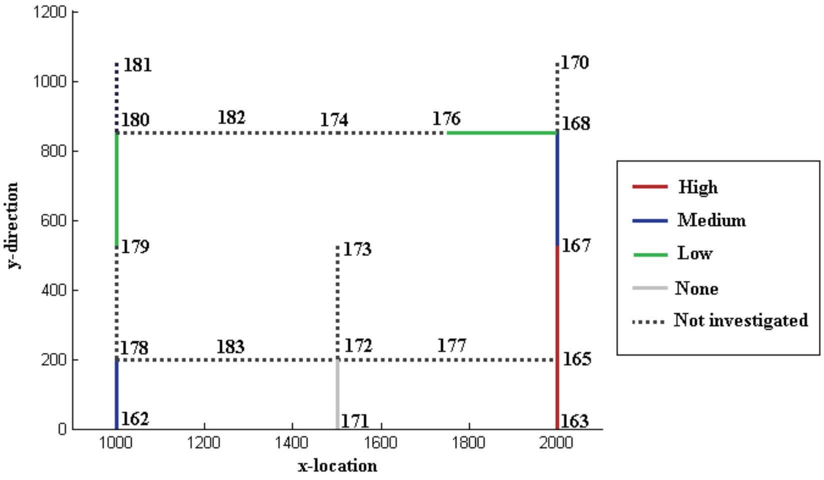

Figure 4 Total sensitivity to blockages in the sewer system

4 DISCUSSION AND CONCLUSIONS

Integrated flood risk analysis requires that risk is measured using a common metric. We have identified core principles and identified two approaches to disaggregating the contribution to risk from different loadings, system components and stakeholders.

The standards-based attribution methodology does not require significant computational resource, but because of the difficulties associated with estimating sewer failure probabilities is limited in practise to risk attribution of loadings only (*i.e.* the contribution towards the total risk from urban rainfall and river flow).

The sensitivity-based attribution methodology can be readily used to explore the contribution from specific infrastructure components (*eg.* flood defences, sewer network). However, drainage systems involve thousands of variables. The only feasible approach to tackling this problem is therefore by hierarchical simplification of the system, with the attribution analysis being applied at several levels, from a very broad scale to identify the main influences on flood risk, to a detailed scale for small well defined problems, to identify the components that are responsible for flood risk.

Approach to integrated flood risk management presented in this paper uses statistical methods to analyse results of series of simulations made by deterministic full-dynamic flood model. Consequent flood damage is interpreted using spatial integration of maximum flood depths linked to corresponding depth-damage curves. Asset management decisions based on sensitivity-based attribution of flood risk are clearly much sounder than those made upon standards-based analysis, which are based on a single event (or a limited number of events).

Future research will look at possibilities for implementing risk attribution methodology at a broader scale on real systems. In these studies, the importance of other groups of elements such as pumps, storage or SUDS will be analysed. Description of damage will be enhanced to include spatially variable housing density and value (using GIS), traffic disruption, health impacts and other damages.

5 ACKNOWLEDGEMENTS

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