Flood risk assessment for infrastructure networks

M.A.E. Emanuelsson N. McIntyre C.F. Hunt R. Mawle J. Kitson N. Voulvoulis

Abstract

A practical framework for flood risk screening was developed to assess the flood risk to water utility assets within the infrastructure network. The tool is a combination of probability and consequence assessments. The first takes into account how probable it is for a particular asset to flood and cause significant damage. The second estimates the level of consequences a flood will have, considering, for example, the level of loss of service, environmental pollution and cost. The consequence assessment is based on a dependency assessment that identifies knock-on effects on other assets within the asset network and assesses the level of consequence they will have. The probability and consequence assessments are combined to produce a risk score that can be used to rank assets in a screening process that aims to assist companies in prioritising the investments required for taking action to reduce flood risk to their assets.

Introduction

In pursuit of integrated, sustainable and effective flood risk management, flood risk estimation frameworks are becoming more sophisticated, more comprehensive and more integrated with other catchment management objectives. This is reflected in national and European frameworks, and recent activity in flood risk management research (Pender, **2006**; Wheater, **2006**; EC, **2007**).

While flood risk evaluation in general is receiving significant attention, relatively little has been done to address the challenge of evaluating flood risk within networks of interdependent assets, where the failure of one asset is dependent on the state of one or more others. For instance, an asset may be affected because of the flooding of a remote but physically associated asset, for example because of widespread loss of power after the flooding of key points in the national grid, as occurred in Gloucestershire in the summer of 2007 (Pitt, **2008**). While frameworks are in place for assessing flood risk, including systems of flood defence assets (DEFRA/EA, **2004**; Dawson *et al*., **2005**; Dawson and Hall, **2006**; Flikweert and Simm, **2008**), these methods cannot be easily extended to cases where the physical interdependence of assets is the essence of the problem.

Asset network flood risk is especially pertinent to the UK water industry. Floods may have impacts in terms of failure of regulatory requirements, human health, environmental quality, remediation cost, and disruption to the provision of water and wastewater services. Impacts may arise directly from the flooding of an asset, or indirectly because of the asset's role within an infrastructure network. For example, the flooding of a pumping station, an access road, an electricity substation or a chemical supply depot may affect the normal operation of dependent treatment works. The potential importance of considering risk arising from the dependencies within asset networks has been recognised by the water industry (Halcrow, **2008**; Water UK **2008**); however, there are no detailed publications of how this might be done in practice.

This paper aims to identify some of the main challenges in quantifying flood risk to water utility asset networks, and proposes a screening (i.e. first-stage) method for prioritising assets in terms of investment to reduce flood risks. The method is demonstrated using a case study from Yorkshire, and the main practical and theoretical challenges associated with the method are discussed.

Flood risk assessment for infrastructure assets

Flood risk assessment is a combination of two aspects: firstly, the probability of a flood event occurring and, secondly, the consequences that flood will have (Gouldby and Samuels, **2005**). An integrated measure of risk is the product of these two components summed over a representative number of independent flood events. While this is conceptually simple, significant theoretical and practical challenges underlie the estimation of both components of risk (Evans *et al*., **2002**, **2006**; Wheater, **2002**, **2006**; Hall *et al*., **2003**; Gouldby *et al*., **2008**; Falconer *et al*., **2009**; Merz *et al*., **2010**). The most relevant general challenges are reviewed briefly here as a background to the proposed framework.

Probability assessment

A fundamental challenge of assessing flood probability is the large range of potentially relevant flood events and associated data limitations (Wheater, **2006**). Types of relevant flood events include fluvial, pluvial and groundwater flooding, and these may occur independently or be associated with a single storm event (or set of storm events). Furthermore, risk may be associated with magnitudes of floods ranging from relatively frequent to unprecedented (Doe, **2004**). The range of potentially relevant events is not, in general, matched by the availability of correspondingly wide-ranging data on flows, inundation extent and depth. Typically, if anything, data for only a small set of floods have been recorded, and instead, climate, hydrologic and hydraulic simulations are relied upon. Even for well-gauged areas, such simulations are necessary to account for climate change and land use change impacts. While fluvial flood mapping is a well-developed discipline, the science of mapping pluvial-type floods is much less developed than it is for fluvial floods (Maksimovic *et al*., **2009**), although indicative surface flooding maps have been produced by the Environment Agency (EA) (**2010**) and as part of the recent Surface Water Management plans. The science of groundwater flood mapping is also relatively undeveloped (Cobby *et al*., **2009**). The limitations in data mean that, in general, a small number of representative floods must be used as the basis for estimations; associated probabilities carry large uncertainty; and groundwater and pluvial-type flood risk has often been discounted or treated nominally (i.e. not numerically) using subjectively based indicators of risk.

Another general challenge in asset risk analysis is related to the scale and precision of flood inundation data. A flood event may inundate a large area, and a broad scale analysis would assign the same or similar risk to everything within that area. The functioning of assets, however, depends on local features, including the locally precise flood inundation depths and durations. In most cases, a precise, local-scale flood inundation analysis is not realistic because of the resource requirements – at least not until the critical assets have been identified by a preliminary level of modelling.

The need to use broad-scale and incomplete information for preliminary local scale risk analysis leads to a two-stage calculation of probability. Rather than simply looking at the estimated probability of the asset being exposed to a flood (as predicted by a flood map or, in the absence of a map, corollary information), it is often appropriate to consider also the *probability of the flood causing significant damage or disruption* to the site, such that there will be 'consequences'. This not only makes allowance for the uncertainty associated with lack of scale and precision of the flood data but also allows the reliability of local asset measures (including their design, operation and condition) to be factored into the probability. Such considerations are established for assessing risk of breaches to flood defences (Hall *et al*., **2003**). Therefore, an important feature of the risk framework presented in this paper is the combination of the probability of a defined flood event and the associated probability of that event having a significant consequence. In the rest of this paper, these two components of probability are termed here 'flood probability' and 'vulnerability'.

Therefore, given quantitative or qualitative data on flood probability, the next challenge is the estimation of vulnerability. Vulnerability, or 'fragility', has received significant attention in the context of condition of UK national flood defence assets (Gouldby *et al*., **2008**). The same level of analysis would ideally be conducted for all infrastructure that has uncertain resilience to a specified flood; again, however, this constitutes a major investment in terms of data collection and is unlikely to be considered appropriate prior to the initial quantification of risk. Consequently, at the risk screening stage, the challenge is to develop relatively rapid indicators of vulnerability. Despite some recent interest (Scheuer *et al*., **2010**) there is relatively little literature on this aspect of the flood risk context, and it will be addressed further in the framework described in the following section.

Consequence assessment

When performing any type of flood risk assessments apart from hydrologic hazard information, it is also necessary to have information about possible consequences of flooding. This information can be used to define high-risk areas, assess benefits (e.g. damage avoidance) or perform cost–benefit analysis for insurance and compensation schemes (Moel and Aerts, **2011**). There is a wide range of consequences of flooding: while most flood risk models quantify consequences in monetary terms (Hall *et al*., **2005**; Kok *et al*., **2005**; Thieken *et al*., **2008**), it is important also to consider social and environmental consequences (Penning-Rowsell *et al*., **2006**; Meyer *et al*., **2009**). For example, in the water industry, obvious consequences of flooding include disruption of water supply, disruption of water treatment, and repair and clean-up costs. However, as well as loss of service, knock-on effects such as contaminated waters, disturbed ecosystems and social distress should ideally also be included.

According to Keeney and Raiffa (**1993**) the selection of criteria must be comprehensive, measurable, complete (cover all aspects of the problem), operational (meaningful in analysis), decomposable (able to be broken into parts to simplify the process) and nonredundant (avoid double counting). The criteria will vary with asset type and type of study and should be carefully selected. As the criteria may not have common units of measurement [for instance environmental impacts, or casualties, are difficult to quantify economically (Meyer *et al*., **2009**)], any attempt to combine them, for the purpose of an integrated measure of risk, will require some judgement.

Network analysis

Another challenge, and the main focus of this paper, is the potential knock-on effect of a flood throughout a network of assets. A limited research has been undertaken into the role of critical infrastructure interdependencies in disaster management (Rinaldi *et al*., **2001**; Streips and Simpson, **2007**; Sultana and Chen, **2007**). Rinaldi *et al*. (**2001**) identify four principal classes of interdependency: physical, cyber, geographical and logical. The physical class of dependency refers to assets whose state is dependent on the output of another. For example, a sludge treatment facility may be physically dependent on the material produced by a sewage treatment works (STW). Cyber dependencies exist if the functioning of an asset depends on information infrastructure. Such a dependency particularly applies to automatically controlled assets, such as drinking water supplies controlled by the water grid system, or flood warning systems triggered by water level gauges. Geographical dependencies exist when a local event affects assets that together form a critical resource. An example of efforts to minimise risk from geographical dependencies was seen after the hurricanes Rita and Katrina in 2005, when the US Energy Policy Act facilitated the construction of new natural gas import terminals in geographically diverse ports (Streips and Simpson, **2007**). Logical dependencies cover a range of alternative dependencies, principally relating to human decisions and resources. For example, availability of staff, pumps and flood defence equipment may depend on the resources being used elsewhere.

As well as classifying the type of dependency, Rinaldi *et al*. (**2001**) referred to the strength of dependency as a ‘tight’ or ‘loose’ coupling. This describes the speed with which an asset is affected by a failed dependency: the more immediate the impact, the tighter the dependency. For example, a water treatment works (WTW) without a back-up generator might have a ‘tight’ dependency on the electrical supply, but if there is a generator on site which can keep the site running in case of electricity cut, the dependency would instead be ‘loose’. Rinaldi *et al*. (**2001**) also classified the nature of the disruptions to asset systems as cascading, escalating and common cause. A cascading failure occurs when a disruption to an asset causes the failure of a component in a second asset. The previous example of loss of electricity supply would be a cascading failure (and this is the type that we are principally concerned with). An escalating failure occurs when an asset is affected by two independent failures, the effect of each failure compounded by the other. For example, the loss of both landline and mobile phone use would severely hamper the coordination of a flood response, but the loss of just one would not be as debilitating. A common cause failure can occur when two assets have a geographical dependency or because the root problem is widespread, such as two WTW within a supply network failing because of the same storm event.

In practice, asset dependencies are not generally explicitly considered in flood risk assessments frameworks, and there are very few explorations of how this might be achieved. One exception is the work of Sultana and Chen (**2007**), who modelled the occurrence of a dam collapsing and its impact on seven other assets: penstocks, the power plant, the water storage and treatment plant, the water distribution system, the power distribution system, and highways. A quantitative analysis of flood exceedance probability was performed for each site, followed by the structural analysis to determine their failure modes for selected flood events. The next step was a qualitative analysis of how one infrastructure item in a network is affected by one or more others, developed into a matrix of logical dependency rules. Depth-damage curves were constructed to represent significant failure modes. This set of data and rules was formalised into a Petri net model (Murata, **1989**) which is graphical, and mathematical modelling language was used to describe distributed systems, where different types of nodes represent transitions (*events*) and places (*conditions*); the nodes are connected and the activation of one can activate others, and tokens (dots moving from node to node) are used to simulate dynamic and concurrent activities of the system.

The methods described in the next section develop the ideas of Rinaldi *et al*. (**2001**) and Sultana and Chen (**2007**) to produce a screening method within which an asset network can be specified and risk to individual and groups of assets can be approximated.

A screening approach for assessing asset network flood risk

The approach (schematic in Figure **1**) is described as 'screening' to indicate that it does not attempt to provide a rigorous treatment of risk and does not provide absolute measures of risk. This would require more extensive information than typically exists about inundation depths and asset network operation under a range of potential flood events. Furthermore, considering the multiple types of assets and asset owners potentially involved, relevant operational information, even if it exists, is unlikely to always be available. Therefore, rather than aiming to be analytically rigorous, the method provides relative and indicative measures of risk, aiming to identify those assets that are at most risk from flooding and those that pose most risk to other parts of the network. Once this screening stage is complete, it is envisaged that a further, more detailed and more focused assessment would follow. The method focuses on the range of assets of concern to UK water utilities (who typically own and operate the infrastructure for both the potable water and the wastewater services).

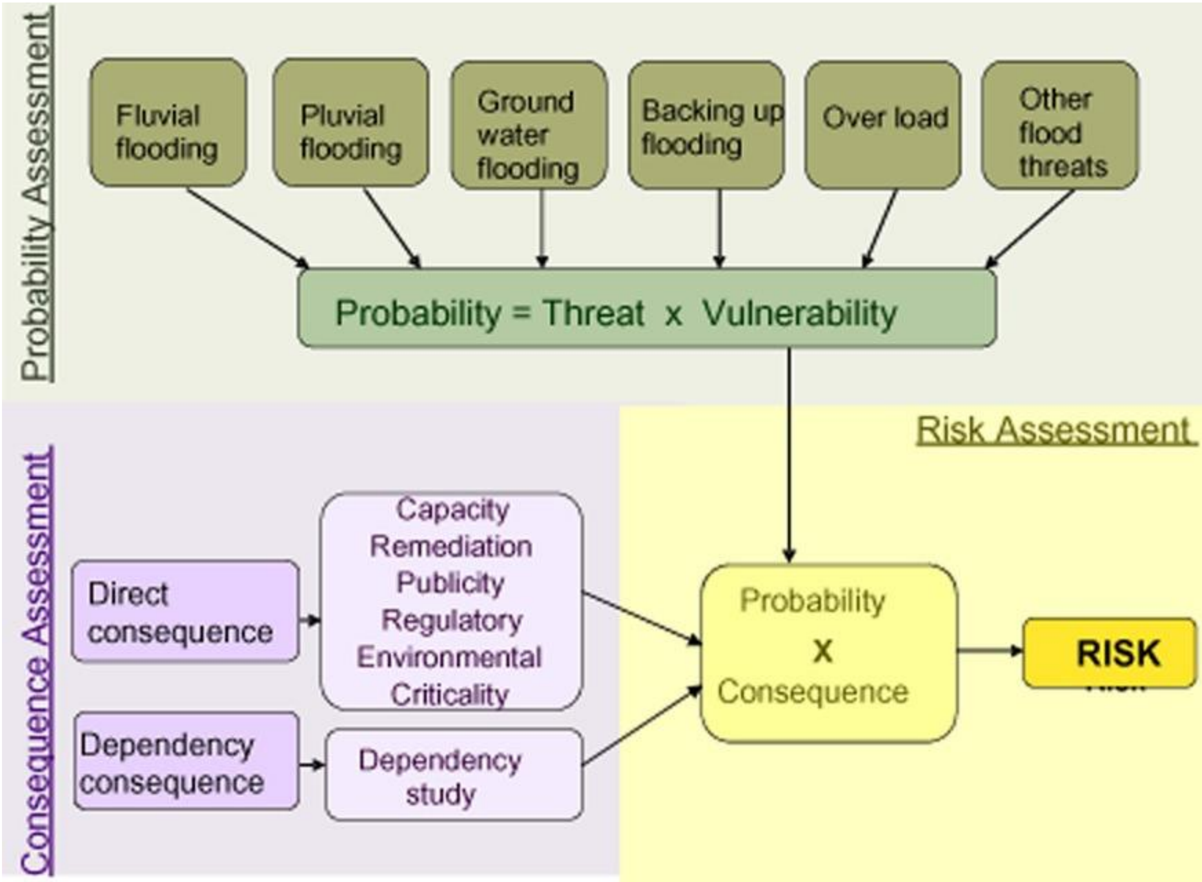

Figure 1: Overall view of flood risk tool, combining probability assessment and consequence assessment.

In this section, we first address the single site case where the source of flood risk is local flooding, independent of the asset network. Some of the fundamental challenges arise here. We then proceed to the network analysis.

Single site analysis

Risk arising from an event may be defined by the probability that the event will occur and lead to damage multiplied by a measure of the damage. The proposed procedure for estimating risk for a single water utility asset is as follows:

1. Estimate flood probability for a sample of relevant flood events. Fluvial flood maps, from which inundation depths can be estimated, are often available in the UK for a number of flood exceedance probabilities, derived within regional and/or local flood risk evaluations, for example through local resilience forums. Data for other types of flooding are usually more limited. Records of storm sewer flooding are kept by the sewerage provider, from which some estimate of flood probability may be made. Despite recent progress in surface water flood mapping (e.g. EA 2010), local-scale surface flood estimation remains difficult because of the high-resolution data required and potential for interactions with sewer flooding (Balmforth and Dibben, 2006; Maksimovic *et al*., 2009). Similar difficulties apply to groundwater flooding (EA 2006). At present, the best source of knowledge about surface and groundwater flood frequency is likely to be (often anecdotal) records of past events. Other flood threats to be considered are backing up of water through discharge pipes and other

pipes connected to receiving rivers, which is mainly a concern for STW, and overloading of incoming water to a STW or sewage pumping station due to flooding or heavy storms in the catchment area.

2. Assess the vulnerability of the site. This aims to reflect the probability of impact occurring. This is scored on a scale between 0 and 1, where 0 indicates there will be no impact and 1 indicates that there will definitely be an impact. This is based on site survey combined with any available records of failure, combined with expert judgement (as is normal practice in high-level flood risk evaluation (e.g. DEFRA/EA, 2004).
3. Identify suitable criteria for assessing consequence. In the UK water utility context, considering the relevant regulations [The Water Supply and Sewerage Services (Customer Service Standards) Regulations 2008; The Flood Risk Regulations 2009; Flood and Water Management Act 2010] leads to the identification of six main categories of consequence: Loss of Service, Need for Remediation, Criticality, Public Perception and Publicity, Regulatory Requirements, and Environmental Pollution. Each of these categories of consequence is assessed using appropriate criteria, and in some cases their subcriteria, defined in Table 1.
4. The degree of consequence for each criterion (or subcriterion) is quantified by a score. Quantification is likely to be straightforward for some criteria (e.g. capacity measured as number of customers served), while for others there may not be an obvious measure or the required data may not be available, and in these cases judgement is needed. The range of scores used is essentially arbitrary, although it must be reasonably consistent over assets and events. Where data limitations preclude the estimation of consequence for each flood event, a consequence might be assumed uniform over a group of events.
5. The importance of each consequence is assessed on a scale from 0 to 1, and the consequence is weighted by this value. This provides the opportunity to judiciously allow for factors affecting perceived risk that are not explicit in the consequences assessment. As an example, special environmental or customer service issues may exist at a particular location which would justify assigning more weight to one criterion. The weighting is applied according to the user's preference and can change between analyses.
6. Following the estimation of (a) a set of consequence scores for each flood event and (b) the estimation of the probability of that event, these may be used to calculate a set of risk scores for that site and that event. These may then be summed to give a total risk score for that site (while recognising the limited significance of summing risk in this way, as discussed after the case study).
7. If required, the analysis could be repeated for further scenarios, for example of climate change or infrastructure developments.

Table 1. Types of impacts considered. Weights are considered at two levels; first, subcriteria within each criterion are weighted against each other, and then the criteria are weighted against each other

Criteria	Measure	Score	Weight	Final score
Loss of service			0.25	0.25
Capacity	Size/capacity	1	1	
Remediation			0.15	0.15

Criteria	Measure	Score	Weight	Final score
Clean-up cost	Size/capacity	1	0.5	
Repair/replacement cost	Age depreciation value	1	0.5	
Public perception and publicity			0.1	0.012
Odour/nuisance	Number of people living nearby	0.4	0.3	
Previous adverse publicity	Any previous adverse publicity	0	0.3	
Sensitive establishment close to site	Table with sensitive establishment	0	0.4	
Regulatory requirements			0.2	0
Previously failed OPA	YW database	0	0.2	
Low pressure (GSS 10)	YW database	N/A	0.1	
Notice of interruption to supply (GSS8)	YW database	N/A	0.2	
Supply not restored (GSS9)	YW database	N/A	0.2	
Internal sewer flooding (GSS11)	YW database	N/A	0.1	
External sewer flooding (GSS12)	YW database	N/A	0.1	

Criteria	Measure	Score	Weight	Final score
Criticality			0.2	0.2
Critical asset	Criticality list	1	1	
Environmental pollution			0.1	0.07
Effluent discharge consent compliancy	Type of discharge consents	1	0.25	
Sensitivity of receiving water	Biodiversity risk tool	0.4	0.25	
Surroundings in term of land use	Table with types of infrastructure	0.4	0.25	
Pollution from trade	TPE/ dilution rate	1	0.25	
Total score				0.686

- GSS, Guaranteed Standard Scheme; OPA, Overall Performance Assessment; YW, Yorkshire Water.

Network analysis

The aim of the network analysis for any water utility asset (A) is, as well as estimating risk to A arising from direct flooding of A, to estimate the risk arising from assets upon which A is dependent; and risk arising from assets dependent upon A. As in the single site analysis, the measures of risk are not absolute; rather, they aim to allow the risk associated with A to be compared with that associated with other analysed assets. The following steps are used, adapting the network analysis ideas of Rinaldi *et al*. (**2001**) and Sultana and Chen (**2007**).

1. Define the boundaries of the network to be analysed, i.e. the scope of the assessment.
2. Identify infrastructure assets within the network that should be included.
3. Define the sample of flood events to be considered for each asset and, for each asset and for each event, estimate the flood exceedance probability and vulnerability. This step is equivalent to steps 1

and 2 in the single site analysis, but note that this may now include assets not under the control of the water utility.

4. Identify types and locations of dependencies and create network diagrams (Figure 2).
5. Assess the strength of each dependency (considering whether it is classed as a 'tight' or 'loose' coupling) and assign a strength score. The precision of the strength score will depend upon the supporting information: if it is based on estimation rather than a more detailed analysis of the dependency, then the score may simply be 1.0 for a tight dependency and 0.5 for a loose dependency, which would act to weigh down the effect of the dependency on the risk.
6. Define the consequence criteria that are relevant to each asset, and quantify the extent and importance of consequence associated with each site for each flood event considered. This is the same as steps 3, 4 and 5 in the single site analysis; however, here it also includes an analysis of the consequences arising from dependencies.
7. For consequences arising from dependencies, adjust the consequence scores by multiplying with the associated strength scores.
8. Quantify risk for each asset by multiplying the adjusted consequence by the relevant probability (as step 6 of the single site analysis).
9. Repeat for any scenarios of interest (as step 7 of the single site analysis).

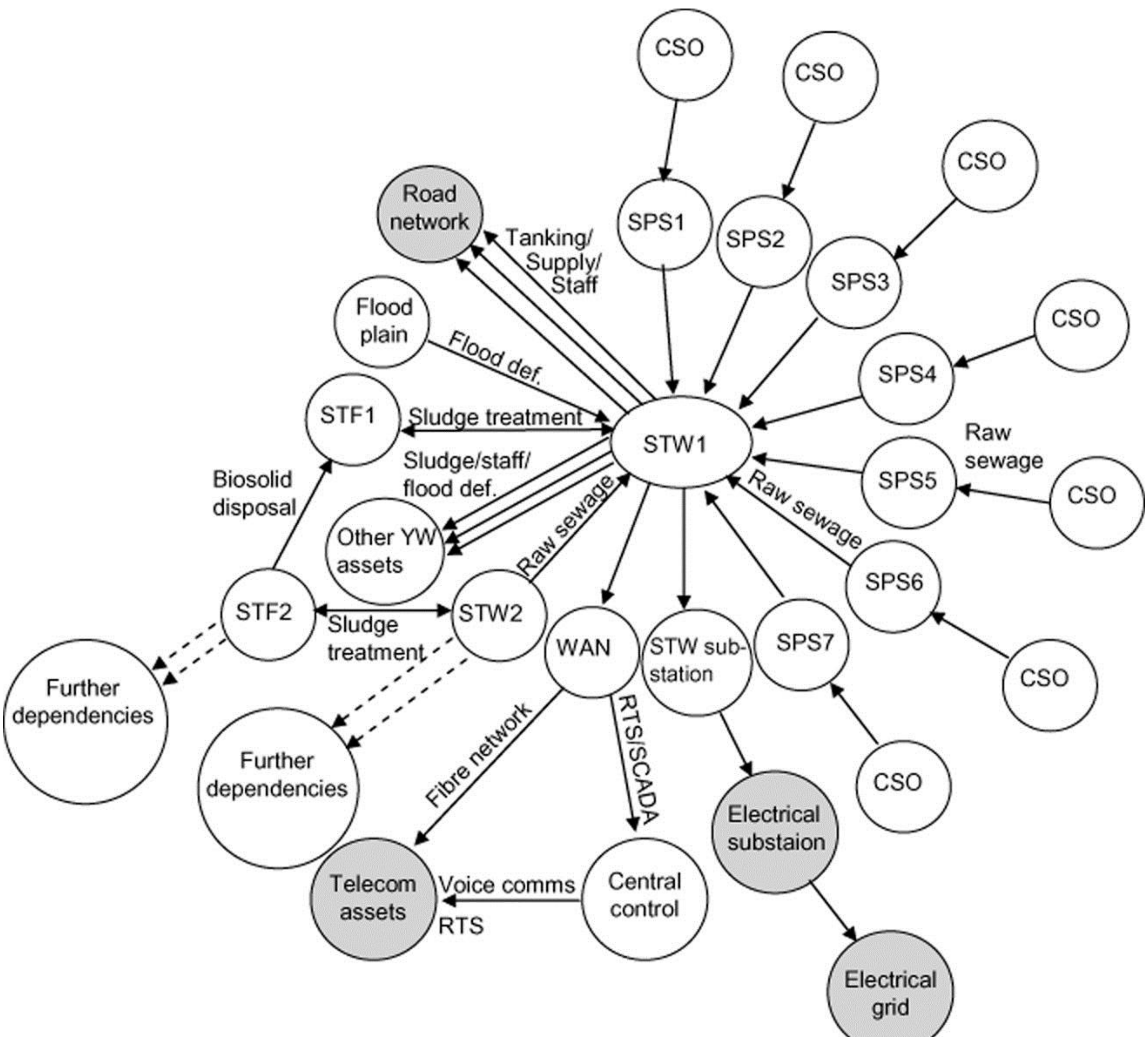

Figure 2: Interdependency network for case study area showing first- to fourth-order dependencies. Assets out of the control of the water company are marked in grey. Arrows pointing towards the asset upon which the first asset is dependent. Arrows pointing in both directions are dependencies going both ways. Dotted lines represent further unspecified second- or third-order dependencies. STF, sludge treatment facility; STW,

sewage treatment works; CSO, combined sewer overflows; RTS, real time system; SCADA, supervisory control and data acquisition; SPS, sewage pumping station; WAN, wide area network; YW, Yorkshire Water.

Case study of Yorkshire Water (YW) assets

The Yorkshire region has suffered several floods in recent years. In particular, in the summer of 2007 it was estimated that around 11 000 homes, 3000 businesses, 23 sewage treatment works, 140 electrical substations and 65 km of roads were directly affected with an estimated cost of £470 M (Risk & Policy Analysts Ltd and Royal Haskoning, **2008**). With events like that in 2007 potentially becoming more frequent in the future (DEFRA, **2006**; Pitt, **2008**), there is pressure on YW and other UK utility companies to be better prepared for floods.

The aim of the case study is to demonstrate the strengths and limitations of the risk screening approach and the challenges arising. Although the study is based on a real network, asset names have been synthesised. The description of the risk assessment follows the network analysis steps listed previously, focusing on a large STW servicing a city in the Yorkshire area, here called STW1. The identified asset network is shown schematically in Figure **2**.

In terms of type of flooding, the case study is restricted to fluvial flooding at STW1 and associated flooding due to backing up of the effluent discharge. The other flood types were not included as they are not likely to present a significant risk in this case; the site is built on a slight slope towards the river so any surface water should either be drained through the drainage system or flow down to the river. Data on fluvial flooding came from the flood maps published by the EA of England and Wales (corresponding to 0.01 and 0.001 exceedance probabilities) and associated peak water levels. This is supplemented by the National Flood Risk Assessment database and by historical records kept by YW. The flood maps indicate that part of the site (approximately 20%) is exposed to flooding at the 0.01 exceedance probability, and the whole site at the 0.001 exceedance probability. Following a review of YW flood records and interviews with operations staff, the site was judged to have 0 vulnerability to 0.01 exceedance probability flooding, but moderate (0.35) vulnerability to 0.001 exceedance probability flooding. Backing-up flooding due to high water levels at the outlet was also considered relevant in the case of the larger flood, although the likelihood was considered small compared with direct inundation of the site, and not independent of it. A nominal vulnerability of 0.1 was used to represent this type of flood, as it is likely that a flood will affect the site but only to a very small extent.

By building a dependency network as shown in Figure **1**, 14 other assets were identified as having first-order (direct) dependencies with STW1 including one two-way dependency (Table **2**). Nine assets are dependent on STW1, while STW1 is dependent on 6, giving 15 direct dependencies to consider. For assets upon which STW1 is dependent, the flood exceedance probability was estimated by following a similar procedure as applied for STW1. There are 14 assets with higher-order dependencies in Figure **2**. These were also included in the analysis but are not listed in Table **2**.

Table 2. Consequence scoring from dependencies

Assets upon which STW1 is dependent	Type	Coupling	Strength score	Consequence (STW1)	Consequence score
STF 1	Build-up of sludge	Loose	0.5	0.69	0.35
Temp. flood defence	Flood	Tight	1	0.69	0.69
Electrical supply	Power shutdown	Tight	1	0.69	0.69
Staff	Operation of site	Tight	1	0.69	0.69
Chemical supply	Treatment	Loose	0.5	0.69	0.35
WAN	Operation of site	Tight	1	0.69	0.69
Assets dependent upon STW1				**Consequence (dependencies)**	
SPS 1	Sewage build-up	Tight	1	0.079	0.079
SPS 2	Sewage build-up	Tight	1	0.024	0.024
SPS 3	Sewage build-up	Tight	1	0.24	0.24

Assets upon which STW1 is dependent	Type	Coupling	Strength score	Consequence (STW1)	Consequence score
SPS 4	Sewage build-up	Tight	1	0.30	0.30
SPS 5	Sewage build-up	Tight	1	0.12	0.12
SPS 6	Sewage build-up	Tight	1	0.09	0.09
SPS 7	Sewage build-up	Tight	1	0.36	0.36
STF 1	Sludge	Loose	0.5	0.06	0.003
STW 2	Sewage transport	Loose	0.5	0.09	0.0018
Final dependency score					1.22

- STF, sludge treatment facility; STW, sewage treatment works; SPS, sewage pumping station.

The six classes of consequences considered are Loss of Service, Remediation, Public Perception and Publicity, Regulatory Requirements, Criticality, and Environmental Pollution, and their perceived magnitudes are represented by the scores included in Table **1** for STW1. A similar table is produced for all assets in this network.

Each class of consequences is estimated according to measurable subcriteria, where some classes have only one while others have several (Table **1**), each being scored on a scale of 0–1. The choice of measures to score subcriteria was based on the availability and accessibility of data and information. Some were straightforward, such as the measure of Loss of Service, which deals with the effect a flood will have on customers. It uses a table adapted from the YW business risk matrix that assigns assets on a five-point risk scale, ranging from Very Low (score 0.2) to Very High (score 1), using measures such as pumping capacity for a pumping station, million litres per day of treated water for a WTW and population equivalent for a STW. The population equivalent of the STW in the case study is in the Very High category and is therefore assigned a score of 1 for the capacity subcriteria (Table **1**).

The Remediation class deals with the cost of restoring the site after a flood. The two subcriteria in this class are the cost of clean-up (measured by the size of the asset) and the cost of repair and replacement (measured by the age depreciation value of the asset). As the STW in the case study is a relatively large and new asset, it is assigned the highest score for both these subcriteria (Table **1**).

Within the Environmental Pollution consequence class, YW created scoring matrices for subcriteria such as 'Pollution from Trade', which is a criterion that applies for STW only. As wastewater from trade population may have a higher chemical oxygen demand than domestic waste water, it will potentially have a more severe effect on the receiving environment (Eckenfelder *et al*., **2009**). The pollution from trade score is obtained by dividing the Trade Population Equivalent for the STW by the dilution rate of the receiving water. An environment and biodiversity risk tool that is a GIS application assessing the impact of YW operations on downstream biodiversity using the river network as a connecting feature, and was already developed at YW, was used for the 'Sensitivity of Receiving Water' subcriterion, while for 'Surrounding in Terms of Land Use', the sensitivity of the type of infrastructure surrounding the asset (for example nearby main roads, schools and hospitals) is used.

The Regulator Requirements subcriteria were selected using the Guaranteed Standard Scheme regulations instituted by OFWAT in accordance with the (Water Supply and Sewerage Services (Customer Service Standards) Regulations **2008** (SI2008/594), and methods for measuring each subcriterion exist at YW. As most of the subcriteria in this class do not apply to STW, the score for the STW in the case study was 0 (Table **1**).

Subcriteria can easily be added or removed according to preference and available information. The method is designed to be flexible and adaptable to different types of asset network and analysis, where additional or different subcriteria may be necessary. The measures used for scoring are determined by the water company and can be changed according to available information and the level of complexity required for the analysis. For example, the Criticality subcriterion is currently measured using an already existing 'criticality list' of YW assets so that an asset on the list will score 1 whereas the rest will score 0, but this is simple to change if more specific information is available. All subcriteria and their measures are listed in Table **1**.

The STW at the centre of this case study (STW1) is relatively large for its type, so it scores fairly highly for many of the subcriteria, with a combined consequence score of 0.69 (Table **1**). However, this considers only its direct consequences, and the next step is to calculate consequence through dependencies. In order to do that a similar table to Table **1** was created for all assets within STW1's dependency network and a combined score calculated; the dependency score for each asset is listed in Table **2**. In this case, before adding up all the consequence scores, they need to be combined with the strength scores for each dependency, which is a measure of how quickly the asset is affected by dependency failures. In the case study, an immediate effect (tight coupling) received a score of 1 while a delayed effect (loose coupling) received a score of 0.5, in fact weighting down the effect of dependency on the overall risk. Once the strength score for each dependency is determined and combined with the consequence of the corresponding asset, all the adjusted consequence scores can be added to give a final consequence score for STW 1 in the case study (Table **2**). The final consequence score for STW 1 is 0.69 from direct consequences and 1.22 from dependency consequences (Table **3**). A limitation of the case study consequence analysis is that, because of the limited information available on potential consequences, the scores are assumed to be independent of the magnitude of the flood; however, they may be varied at a refined stage of analysis.

Table 3. Risk scoring for case study STW1

Flood type	Vulnerability	Probability	Direct consequence	Direct risk	Dependency consequence	Dependency risk	Combined risk
Fluvial 0.01	0	0	0.69	0	1.22	0	0
Fluvial 0.001	0.35	0.00035	0.69	0.00024	1.22	0.00043	0.00067
Backing-up 0.01	0	0	0.69	0	1.22	0	0
Backing-up 0.001	0.1	0.00001	0.69	0.0000069	1.22	0.000012	0.000019

- STW, sewage treatment works.

Finally, the consequence scores are multiplied by the probability of the event occurring to produce a set of scores that indicate the risk to STW1 associated with each dependent asset, the direct risk to STW1 and also the combined risk. The combined risk for STW1 is 0.00067 for fluvial flooding and 0.00019 for backing-up flooding (Table **3**). These have no units; rather, they are relative measures for prioritising a more detailed analysis.

In a screening process the previously explained procedure is followed for all assets of interest, for example all STW in a specific catchment or all STW within the control of a water utility company. The score obtained for each asset is then used to rank the assets according to flood risk and ultimately identify which assets would benefit most from post-screening analysis and potentially flood mitigation measures. After selecting the assets of interest it is then useful to go back to the scoring process in order to identify why the selected assets received a high score, whether it is because of high probability of flooding, high vulnerability of site in case of flooding, a high number of dependences or even a combination of these factors. This information is critical for the next step, which would be further analysis potentially leading to a decision on mitigation measures for the selected sites.

Discussion

The proposed method aims to provide a practical framework for risk screening both under baseline conditions and incorporating climate change, compatible with information readily available to a water utility. The risk scores aim at quantifying relative risk, unburdened by some of the theoretical requirements of a rigorous risk assessment. In implementation, as with any evaluation that relies on judgements in addition to, or instead of, hard data, emphasis must be placed on the consistency and transparency of the judgements.

A major theoretical issue is that the method incorporates no process for considering interdependence between events, so there is a danger of double-counting when summing of risk over events. This problem may arise when considering floods at more than one asset and when considering different types of flood (Lamb *et al*., **2010**). In cases where the events are considered to be strongly dependent (e.g. fluvial flooding is considered likely to occur simultaneously with pluvial flooding, or a pumping station is likely to flood at the same time as a dependent sewage treatment works) then both occurring together should be treated as a single event with associated joint exceedance probability, although modelling frameworks do exist for integrated modelling of different flood types (Maksimovic *et al*., **2009**; Chen *et al*., **2010**). Similarly, if two assets within a network are vulnerable to the same event and have some common consequences, it would not be appropriate to assess them independently; rather, the effect of that event should be assessed holistically considering the geographical and escalating-type consequences, as classified by Rinaldi *et al*. (**2001**). Alternatively, for the purpose of sensitivity analysis, the vulnerability of one of the two sites might be removed in order to identify the risk arising from the second site independent of the first. In a further stage analysis, more rigorous frameworks for treating dependencies might be considered (Lamb *et al*., **2010**).

The issue of double-counting of risk also arises when considering one type of event (e.g. fluvial) at one site for different exceedance probabilities. The ideal procedure for calculating risk is to integrate the probability density multiplied by the consequence over the full range of event magnitudes (commonly implemented using depth-damage curves). However, in general practice, and in the case study, neither the probability density function nor the consequences are known over the full range of event magnitudes – instead, the available information usually allows only a small number of events to be considered. The case study implicitly treated the small number of events (only two) as independent occurrences and representative of the full range of relevant fluvial events. Clearly this does not allow the risk score to be interpreted in absolute terms, for example as an annual expected damage, but as long as the method is applied reasonably consistently across assets, it does permit comparative analysis.

Otherwise, the applicability of the proposed approach is mainly limited by knowledge of the network dependencies, sources of flood risk and ability to reflect the true complexity of the network in an operational model. For example, localised pluvial flooding is often extremely unpredictable, yet it may have a significant role in the operation of an asset network, for instance by making a road impassable. Such is the potential size of the network and the quantity of information required to assess the vulnerability of, say, each stretch of road that it seems unrealistic to aim to capture this level of detail despite its being potentially critical. Local plans with this information do exist for some councils and can be very useful, but even where information exists, its provision is another unpredictable factor. Given that the network includes roads and associated drainage, power supply networks, telecommunications, flood defences and water utility assets, even if data exist to allow the vulnerabilities and dependencies to be quantified, there is no requirement in the UK for the relevant infrastructure owners to share this information for the purpose of planning. Nevertheless, by implementing a high-level screening approach, as described here, the need for particular items of information, and the need to focus on particular elements of the network, may be exposed and, hopefully, acted upon.

The proposed framework, once developed beyond the screening stage, provides an opportunity to identify the operational and planning strategies that minimise risk. As a result of the screening process, company assets can be ranked according to flood risk by using the scoring system. This will allow for prioritisation of investments to reduce the flood risk to their assets, where a wide range of aspects have been taken into account including knock-on effects on other assets. Because of the multiple criteria approach used to define risk within the framework (Table **1**), multicriteria analysis may be the most appropriate method to use. This type of decision making allows for ranking of alternative strategies, for example increasing the resilience of selected assets, based on their impact across the given criteria. An impact score reflecting the performance of an alternative against a given criterion can be laid down in a performance matrix (Balasubramaniam and Voulvoulis, **2005**). Multicriteria analyses are widely used for various risk assessments and decision-making processes (Keeney and Raiffa, **1993**; Malczewski, **2006**; Munda, **2006**) and have in a few cases previously been used in flood risk assessments (e.g. RPA, **2004**; Meyer *et al*., **2009**).

Conclusions

Like other service providers, water utilities rely on infrastructure networks. As well as their own assets, this includes infrastructure that, for example, provides supplies of power and chemicals, and the communication and transport networks. Hence, the scope of evaluating flood risk to water and wastewater service provision should ideally extend beyond individual water utility assets to the broader infrastructure network. This paper has described and demonstrated a screening approach to assessing flood risk to water utility assets within the infrastructure network. The approach was applied to a case study based on part of Yorkshire, illustrating the consideration of different dependencies within the network in the risk evaluation. This helps identify potentially critical assets within the network, which can then lead to a more detailed and more focused analysis. Challenges for using this approach, and for flood risk evaluation in general, are identifying and representing the complexity of the infrastructure network and the full range of risks in face of limited data availability.

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