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Practical Paper

Alleviating the flood risk of critical water supply sites: asset and system resilience

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ABSTRACT

Flooding can have severe impacts on the water supply services and adaptation responses for the provision of high-quality water supplies are necessary to cope with the risks exacerbated by climate change. This paper explores the planning process for adaptation strategies, emphasizing current research and modelling constraints and comparing resilience strategies. The flood hazard, vulnerability and impact were assessed based on information provided by the Environment Agency, local knowledge and network modelling of outages. Improvements in flood estimation were suggested to extend the range of scenarios analysed and the geographic cover and scope of models, whilst reducing and quantifying associated uncertainty. For evaluating consequences of widespread flooding, information on joint flood probabilities would be relevant, particularly where sites are interconnected. Considering the uncertainties in the approach, two strategies were explored to manage the flood risk, i.e. enhanced asset and system resilience. Low-regret options designed to protect a site from flooding were chosen and, where the population at risk is high, those were complemented with long term strategies for increased robustness of supply network to a multiplicity of risks.

Key words | adaptation, asset management, flood mitigation, flood risk, resilience, water supply network

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ABBREVIATIONS

AWS	Anglian Water Services
DTM	Digital Terrain Model
EA	Environment Agency
LiDAR	Light Detection and Ranging
OS	Ordnance Survey
SEMD	Security and Emergency Measures Direction
WTW	Water Treatment Works

INTRODUCTION

The flooding risk, which is likely to increase with climate change (Hulme *et al*. 2002; Evans *et al*. 2008; Mokrech *et al*. 2008), can have severe implications across the whole range of society, economy and the environment (e.g. Mokrech *et al*. 2008; Pitt Review 2008). From the water industry point of view, flooding may cause interruption or contamination of supplies. As a response to this threat, a flood-proofing message has emerged emphasizing the need to plan for the higher levels of risk now emerging by taking a fresh look at vulnerability of infrastructure and enhancing flood resilience (e.g. Pitt Review 2008; Water UK 2008). This is in line with the Stern review (2007) recommendation that adaptation is crucial to deal with the unavoidable impacts of climate change to which the world is already committed (Hulme *et al*. 2002). Adaptation options should reduce vulnerability to the full

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range of historic variability in order to be robust to future change (Wilby *et al.* 2007). Moreover, even with stable climatic conditions the need for effective flood mitigation measures would not diminish (Marsh & Hannaford 2007).

Driven by the legal requirements of the Security and Emergency Measures Direction (SEMD) and those of their customers, Anglian Water Services (AWS) is planning protection of the key water supply sites from flooding (AWS 2009) under the scope of the PR09 periodic review. To support the water industry, Ofwat provided guidance to assess and manage asset flood risk (Halcrow 2008). One of the major challenges was to make sure that water services are resilient enough to cope with extreme events. This paper presents the methodology used to prioritize the need for risk management identifying the assets at risk, evaluating the consequences of flooding and assessing flood hazard and vulnerability. The analysis considers uncertainties in the approach. Two options to improve resilience are discussed: enhancing asset resilience and system resilience. The former is the design or modification of a site or building so that it is able to withstand the effects of a flood and protect the property (Halcrow 2008). The latter refers to the capacity to provide alternative sources of supply to restore an acceptable level of service reflecting the characteristics of the supply system as a whole.

Case study area

AWS provide water to 4.2 million people in the geographical area shown in Figure 1 (AWS 2007).

The greatest challenges to the provision of high-quality water supply with regards to future flooding are as follows.

- The region includes the lowest-lying area in England and Wales where a quarter is below sea level. Increased storminess and sea level rise will bring the potential risk of more flooding.
- There is a concentration of intensive arable agriculture and future increased rainfall intensity may lead to the deterioration of the resources or contamination of supplies as a result of surface run-off.
- Around one million new homes are expected in the next 25 years (AWS 2007), which further increases pressure on the expected levels of service.

Method to identify the sites at risk from flooding

Identification of potential assets at risk

Operational assets at risk were screened using information provided by the Environment Agency (EA) complemented with local knowledge. The EA data are intended to be used by

Figure 1 | The Anglian region.

utility companies to understand the flood risk to infrastructure and services (EA 2006). The user-friendly tools show the flood extent in the event of flooding from rivers and the sea and are applicable to the whole region. They provide information for the return period that instigates adaptation responses; because, although flood risk management typically considers timescales of 20 or 30 to 50 years (UKCIP 2006; Defra 2007), there is a greater emphasis on appraisal of policies and schemes over a longer timescale of 100 years that define the medium term risk (Defra 2007). The national guidance on the return period is important given the reliance of water supply assets on services which may also be disrupted such as power and chemical supplies.

The sites analysed were surface water and groundwater sources and water treatment works (WTW). To protect public health, wastewater sites with potential long flood recovery periods that are upstream of abstractions which have a low storage capacity were also considered. The EA flood extent was overlaid with these sites to screen the ones at risk. Buffer zones were applied to account for uncertainties on the location and size of the assets and on the flood extent to ensure that sites at risk are not excluded.

Evaluating system resilience – the robustness of the supply network and the impact of asset failure on the water supply

The identified sites at risk were prioritized given the potential impact of asset underperformance or failure on interruption to water supplies, which depends upon the system interconnectivity and local resource availability in terms of quantity and quality. MISER, registered trademark of Tynemarch Systems Engineering Ltd, is a decision-support tool for optimal water management, asset and resource planning widely in use by a large number of UK water companies. MISER (Figure 2) was used for a failure consequence modelling (Henriques & Fowler 2009) to explore the location and population affected by an outage in 2015/2016 under current and planned future system resilience. Two types of simulation were carried out: an individual outage of the selected sites at risk and multiple simultaneous failure events due to potential widespread flood events. Average demand forecast was used and demand seasonality was accounted for if significant (e.g. holiday peak). Climate change induced patterns in consumption and reduction in water availability were assumed not to be significantly different from present (Henriques *et al.* 2008).

Assessing asset resilience: flood hazard and vulnerability

Asset resilience was evaluated for the sites potentially at risk from flooding with high consequences to the provision of water supplies. The flood depth was inferred from the flood extent and digital terrain models (DTM). The flood extents were obtained for a range of return periods, in line with Defra (2006*b*), from the EA flood maps and/or detailed hydraulic and hydrological models, which were derived from a variety of DTM. Given the time and resource limitations, the DTM used to infer the flood depth consisted of the Ordnance Survey (OS) Landform Profile and the Light Detection and Ranging (LiDAR) data. The former, with a vertical accuracy of 1 m, was available for the whole region; the latter with 25 cm accuracy, whose geographic cover is being extended, was used where available from the EA.

A sensitivity analysis of flood hazard was carried out to the inevitable effects of climate change, given the use of long timescales in the analysis. EA model outputs from a sensitivity testing of the flood map using a 20% allowance for peak flows over a 100-year period, which simulate a climate change scenario, were used. The 20% band is based on the work of Reynard *et al.* (1998, 2001, 2005) and is recommended by the Planning Policy Statement 25 (2006) and Defra (2006*a*). This will be superseded in 2009 by the results of the EA project on 'Regionalised impacts of climate change on flood flows'.

Vulnerability of assets to flooding was assessed combining the flood hazard information and local knowledge with site visits to determine the risks to the equipment and the resources. Information gathered included sources and pathways of flooding, asset characteristics, location/height of sensitive equipment and existing/planned site defences and national flood defences making use of the EA National Flood Risk Assessment.

Limitations in the approach to identify sites requiring risk management

This study permitted identifying further research and model development/improvements beneficial for future flood risk

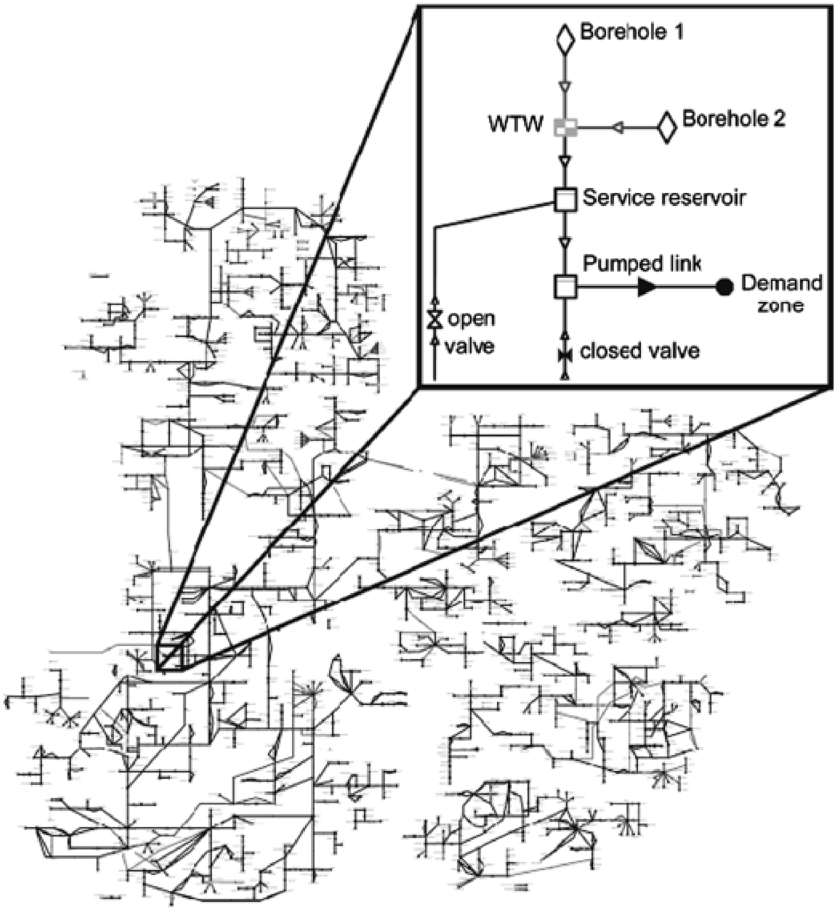

Figure 2 | Anglian Water Services MISER schematic.

assessment (Table 1). The EA modelled flood extents could be updated with more types of flooding and improved DTM to explore a wider range of flood probabilities and scenarios across an extended geographic region.

Enhancing flood resilience

Improving asset resilience in the face of uncertainty

In order to plan for adaptation options, it is fundamental to consider uncertainty, namely in a changing future, and how this uncertainty impacts on the decisions (Willows & Connell 2003). A site-specific analysis was carried out to choose robust and cost-beneficial measures, i.e. low-regret options which allow an asset to operate while it is flooded protecting the equipment and preventing contamination of supplies. Adaptable and low-regret responses were favoured to avoid maladaptation. Construction of embankments was the preferred solution, but others included building walls, flood proofing buildings and improving site drainage. Adaptability was incorporated in the responses which include options for incremental enhancements to be made at minimal cost (e.g. raising embankments).

The height of the defence was based on the estimated flood depth with a freeboard to cope with uncertainty. To facilitate the identification of the adequate level of freeboard protection, a sensitivity analysis to the cost of the protection was carried out and 1 m was found to be cost effective (Figure 5). Increasing the freeboard further was considered not to be practical and to have aesthetical implications particularly in urban areas with potential planning permission issues. Moreover, if the uncertainty is very high, a complete relocation of assets or improved system resilience may be more suitable due to potential large-scale disruption.

Table 1 | Limitations in the flood risk assessment carried out

Limitations	Significance/Risk	Method used to (partially) overcome the limitation
The flood extents do not yet consider pluvial and groundwater flooding.	Pluvial flooding can have severe consequences as illustrated by the 2007 UK summer floods (Pitt Review 2008) and is important due to increased risk from surface water flooding in the future (Evans *et al.* 2008). Groundwater flooding is significant in some parts of the Anglian region.	Flooding history was captured to identify the sites at risk.
The EA flood extents were derived from topographic data with low accuracy.	Important for correct screening of sites at risk.	Expert local knowledge on the geography and topography of the sites was used to verify the sites considered at risk.
High uncertainty on estimated flood depth. This is due to the inaccuracy and mismatch of the DTM used to model the flood extent and to infer the depth from that extent.	The average estimated depth for the sites at risk is 0.4 m; but the estimates with LiDAR are, on average, 0.05 to 0.68 m higher than those estimated with the OS data ($\alpha = 0.05$, $n = 38$). The high uncertainties and lack of their quantification can result in the choice of inappropriate mitigation options.	Adaptation options that cope with depth uncertainties were chosen.
Data for a range of return periods (e.g. Figure 3) were only available for 4% of the assets at risk.	Important to choose cost-beneficial mitigation options that consider the life span of the asset.	Flood hazard probability was not considered due to scarce and uncertain data.
One single climate change scenario available for a small number of sites.	To ensure that policies adopted now are suitable and do not limit future options.	1:1000 return period was assumed as a surrogate for the impacts of climate and socio-economic change in the medium term as inferred from the sample in Figure 4.
No consideration of future socio-economic changes.	As above. Future flooding depends not only on climate change but also on socio-economic changes (Reynard *et al.* 2001; Defra 2007; Wilby *et al.* 2007; Evans *et al.* 2008; Mokrech *et al.* 2008) such as urbanization and land management.	

This emphasizes the need for reduced and quantifiable uncertainty in the tools used, as defended by Wilby *et al.* (2007), to better inform the risk mitigation process.

The efficiency of enhanced asset resilience

An outage was modelled with MISER simulating the situation before and after the implementation of the mitigation options. This allowed assessment of the population exposed at risk and if the SEMD requirements would be met in a catastrophic event. Flooding joint probabilities are not yet available from the Defra/EA 'Spatial Coherence of Flood Risk' project and Keef *et al.* (2009). Therefore, the simulation assumed that all the sites at risk from flooding in a given catchment would fail simultaneously. The selected catchments represent a 'worst-case' scenario where the whole hydrological unit is affected by widespread flooding. Simultaneous outages of sites with common flooding history were also simulated.

Currently, flooding of seven catchments poses risk to a population of over 50,000, which threshold is defined by the SEMD. Options to enhance asset resilience were not proposed for the assets in catchments I, K, M, O, P, Q, R, S, T and U because the MISER results for individual outages showed that the risk to the population is low due to existing system resilience. With the proposed enhanced asset resilience, the population at risk is below target (Figure 6), confirming the suitability of the chosen options under this simultaneous outage scenario.

Robustness of enhanced system resilience to flooding

In order to manage the flood risk building adaptive capacity and guide long term planning, enhancing system resilience was explored. It has advantages over asset resilience because it is more robust to uncertainties and protects the customers not only from flooding but also from drought and lower

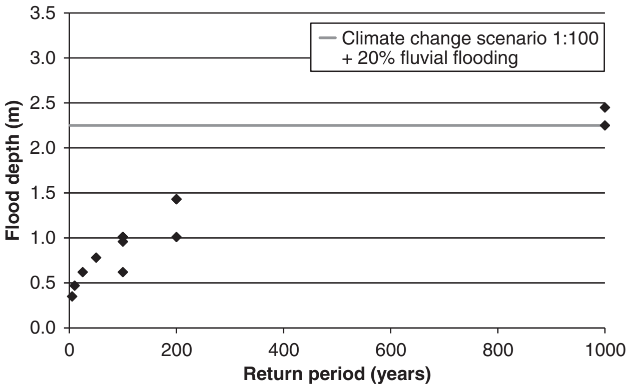

Figure 3 | Flood frequency relationship for an asset showing flood depths for a range of return periods and a climate change scenario (1:100 + 20%). The flood extents for a return period greater than 100 years were simulated by more than one model that covered the geographical area in question.

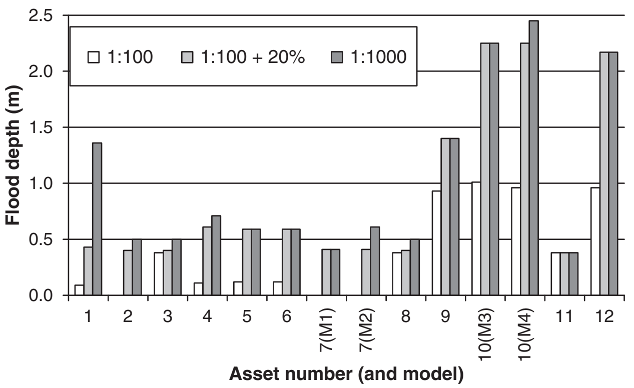

Figure 4 | Flood depth for 12 assets. The flood extent of assets 7 and 10 was simulated by two models. The fluvial 1:100 + 20% event has a probability of happening between the 1:100 and the 1:1000 events, the depths of which differ by up to 1.5 m.

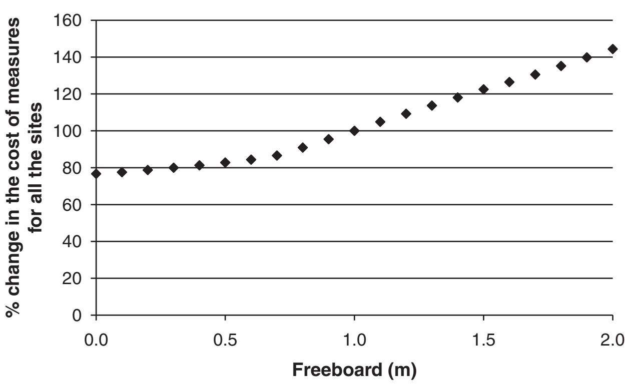

Figure 5 | Sensitivity analysis of the freeboard used on the cost to protect the assets. 1 metre freeboard corresponds to 100% of the cost. The cost is less sensitive to the freeboard if lower than 0.7 m due to fixed costs such as for contractors, and preparing ground conditions and foundations.

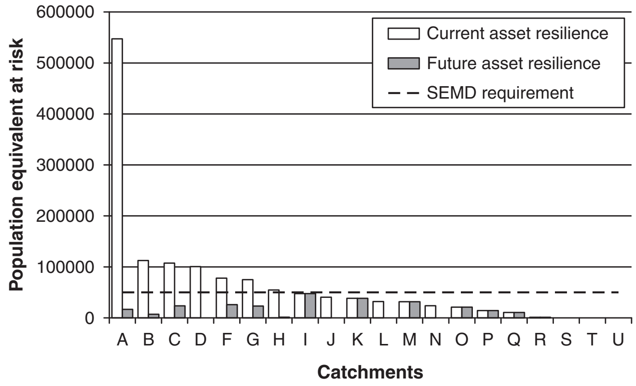

Figure 6 | Population equivalent at risk in case of widespread flooding. Results shown per catchment before and after implementation of flood mitigation options.

probability events such as fire and significant pollution incidents, creating 'win-win' situations. Local solutions, typically the least costly that can be delivered in the short term, were considered such as accelerating the delivery of proposed supply-demand projects, duplicating infrastructure and increasing connectivity. MISER modelling with single outages was carried out to optimize measures for enhanced system resilience. The costs of these measures were significantly higher than those to improve asset resilience; i.e. up to 140 times greater, only being justifiable when the population at risk is greater than 30,000.

The ability of the proposed improved system resilience to provide robustness to the system was modelled and analysed for distinct examples (Figure 7). The north-east coast is characterized by relatively small WTW with good interconnectivity and dual sourcing options. Current and future

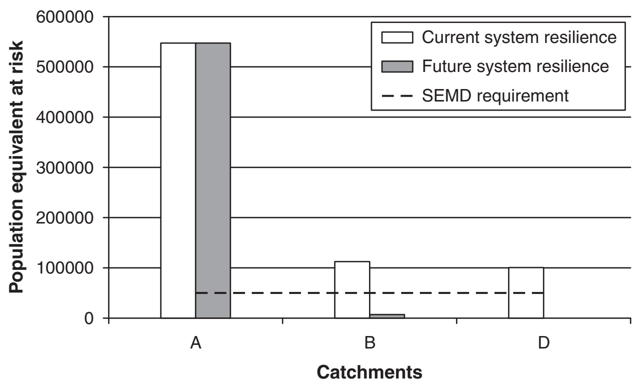

Figure 7 | Population equivalent at risk in case of widespread flooding for three example catchments before and after implementation of improved system resilience.

system resilience may be compromised by the wider impact of flooding likely to affect several sites in catchment A (Figure 7). Securing supply to the customers also involves increasing asset resilience at the major sites (Figure 6).

By contrast, the south-west part of the region contains a series of systems in which large populations are dependent for supplies on single treatment works. As a result, enhancing the system resilience at the major supplies in catchments B and D significantly reduces the population at risk, even in a widespread flood event (Figure 7). This suggests there is not a direct need to implement flood mitigation options at those sites as opposed to the north-east coast. However, improved system resilience schemes should be complemented with enhanced asset resilience. Because some system resilience solutions strategically consist of supply-demand schemes being brought forward, future growth will gradually erode the resilience these schemes provide. Therefore, providing full asset resilience may prevent interruptions to the supply of water in the long term whilst providing other benefits in the short term such as protection of equipment avoiding recovery costs, the ability to manage temporary loss of system resilience and protection from potential contamination of supplies with flood waters or run-off from the agricultural areas.

CONCLUSION

AWS is adapting to cope with extreme flood events in a changing climate avoiding potential interruptions and contamination of water supplies. The method prioritized the water supply sites at risk with impact to the customers. Double jeopardy was considered such as potential contamination of resources by wastewater sites. Network interconnectivity was found to provide additional resilience which resulted in a requirement for less intensive engineering solutions. The analysis used the best available regional tools and identified further challenges in flood estimation such as to explore alternative scenarios and probabilities, reduce and quantify uncertainties, extend the cover of the models, simulate the major flood types and estimate joint flood probabilities. To overcome the uncertainties site knowledge and the choice of appropriate adaptation options was critical.

Both options to improve asset and system resilience were considered. Suitable measures are cost-efficient, low-regret, adaptable and/or multi-purpose. The MISER model was used to optimize the resilience measures. Single outages were applied where populations are dependent for supplies on single treatment works. Where there is good interconnectivity and dual sourcing options, it became important to evaluate the robustness of the system to simultaneous outages likely to occur due to a widespread flood event. Enhanced asset resilience was the favoured option. Improved system resilience, more robust to uncertainties associated with a number of drivers and responses to flood risk, was only justifiable for large population centres as it is costly. Improved asset resilience was found to be complementary to system resilience because it provides asset and resource protection and, where supply network interconnectivity exists, it also prevents erosion of resilience due to potential widespread floods.

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