SURFACE WATER FLOOD WARNINGS IN ENGLAND: OVERVIEW, ASSESSMENT AND RECOMMENDATIONS BASED ON SURVEY RESPONSES AND WORKSHOPS

Susana Ochoa-Rodríguez (corresponding author)
PhD student, Urban Water Research Group, Imperial College London, United Kingdom
Telephone: *+44 (0)20 7594 6018*
E-mail: *s.ochoa-rodriguez@imperial.ac.uk*
Address: *Skempton Building, Imperial College Road, London, SW7 2AZ, United Kingdom*

Dr Li-Pen Wang
Postdoctoral Researcher, Hydraulics Laboratory, KU Leuven, Belgium

Laurie Thraves
Policy Manager, Local Government Information Unit / Local Government Flood Forum, United Kingdom

Dr Andy Johnston
Chief Operating Officer, Local Government Information Unit / Local Government Flood Forum, United Kingdom

Dr Christian Onof
Reader in Stochastic Environmental Systems, Imperial College London, United Kingdom

A former version of this paper was presented at the "International Conference on Flood Resilience: Experiences in Asia and Europe", held in Exeter, UK, between 5th and 7th September 2013. This new version contains more survey results, a more detailed analysis of them and additional details on the methodology.

This article has been accepted for publication and undergone full peer review but has not been through the copyediting, typesetting, pagination and proofreading process, which may lead to differences between this version and the Version of Record. Please cite this article as doi: 10.1111/jfr3.12195

SURFACE WATER FLOOD WARNINGS IN ENGLAND: OVERVIEW, ASSESSMENT AND RECOMMENDATIONS BASED ON SURVEY RESPONSES AND WORKSHOPS

Susana Ochoa-Rodríguez[1,*], Li-Pen Wang[2], Laurie Thraves[3], Andy Johnston[3], Christian Onof[1]

[1] Imperial College London, United Kingdom; [2] KU Leuven, Belgium; [3] Local Government Information Unit/Local Government Flood Forum, United Kingdom;
[*] *Skempton Building, Imperial College Road, London, SW7 2AZ, United Kingdom; Tel: +44 (0) 20 7594 6018;*
E-mail: s.ochoa-rodriguez@imperial.ac.uk

ABSTRACT

Following extensive surface water flooding (SWF) in England in summer 2007, progress has been made in improving the management and prediction of this type of flooding. A rainfall threshold-based Extreme Rainfall Alert (ERA) service was launched in 2009 and superseded in 2011 by the Surface Water Flood Risk Assessment (SWFRA). Through survey responses from local authorities (LAs) and the outcome of workshops with a range of flood professionals, this paper examines the understanding, benefits, limitations, and ways to improve the current SWF warning service. The current SWFRA alerts are perceived as useful by district and county LAs, although their understanding of them is limited. The majority of LAs take action upon receipt of SWFRA alerts and their reactiveness to alerts appears to have increased over the years and as SWFRA superseded ERA. This is a positive development towards increased resilience to SWF. The main drawback of the current service is its broad spatial resolution. Alternatives for providing localised SWF forecast and warnings were analysed and a two-tier national-local approach, with pre-simulated scenario-based local SWF forecasting and warning systems, was deemed most appropriate by flood professionals given current monetary, human and technological resources.

KEYWORDS
Emergency responders; flood forecasting; flood risk management, flood warnings, rainfall alerts, surface water flooding; urban flooding; pluvial flooding.

BACKGROUND

Flood risk management in the UK has historically focused on fluvial and coastal flooding. However, the flooding events that affected the UK in the summer of 2007 brought into sharp focus the imminent risk imposed by surface water flooding (SWF) and the need for an improved approach to its management. In the context of this paper (and in general in the UK), SWF is defined as an exceedance of the capacity of the local drainage system due to heavy rainfall; hence it is also referred to as 'pluvial flooding' (see Parker *et al.* (2011), EA (2015)). When this happens, rainwater escapes from or cannot enter the drainage system -including the ground-, thus remaining on or flowing over the surface. The floods of 2007 were the largest peacetime emergency since World War II, inundating 7,300 businesses and 48,000 houses, causing 13 deaths and resulting in £3.2 billion in damage (UK Parliament, 2010b). The Government commissioned Sir Michael Pitt to undertake an independent review of these flood events which revealed that two thirds of the damage in urban areas was caused by SWF, a type of flooding for which no models, forecasts, warnings or management strategies existed (Pitt, 2008). Besides identifying surface water as a primary cause of flooding in the UK, the review called for a range of actions including clearer roles and responsibilities for SWF risk management and better modelling, mapping, forecasting and warning for this type of flooding.

The Government accepted all of Pitt's recommendations and since then has sought to improve the management of this type of flooding, a challenge given its rapid onset and localised nature. The recommendations that required legislation, including clarification of roles and responsibilities, were implemented through the Flood and Water Management Act 2010 (UK Parliament, 2010a). This Act required local authorities (LAs) to take a 'leadership role' in the management of local flood risk, including SWF, both in the spatial planning and the emergency planning spheres. Taking on this new role constitutes a significant challenge for LAs, especially in the face of current budget reductions, and has seen them lead a drive for better information about local flooding and better tools for its management.

With regard to the technical recommendations, great efforts have been made to model, map and forecast SWF. The Environment Agency (EA) and the Met Office have joined forces to enhance the general flood forecasting capability and to develop SWF forecasting and warning systems for England and Wales. The first step in this direction was the 1st generation Extreme Rainfall Alerts (ERAs) which were piloted between July 2008 and April 2009 and then issued operationally by a new joint Met Office-EA Flood Forecasting Centre (FFC). These alerts were based on national average rainfall thresholds likely to lead to SWF and were issued at county level to Civil Contingency Act Category 1 and 2 emergency responders (UK Parliament, 2004) including LAs, emergency services and utilities companies. The ERA thresholds were established based upon the assumption that exceedance of 1:30 year design rainfall intensities was likely to overwhelm urban drainage systems, leading to SWF. Considering this, thresholds corresponding to the average rainfall depths for durations of 1, 3 and 6 hours and return period of 1:30 years for eight UK cities were adopted (the adopted values, rounded to the nearest 5 mm, were, respectively, 30 mm / 1 h, 40 mm / 3 h, and 50 mm / 6 h) (FFC, 2010). An ERA 'Guidance' was issued when the probability of these thresholds being exceeded was estimated to be over 10 % and an 'Alert' was issued at 20 % or greater probability. Although the ERAs proved generally useful to recipients, they did not accurately reflect SWF hazard nor risk in all areas (Parker *et al.*, 2011; Hurford *et al.*, 2012).

In October 2011, the ERAs were superseded by the 2nd generation Surface Water Flood Risk Assessment (SWFRA). The SWFRA is the result of an objective assessment done with the Surface Water Flooding Decision Support Tool (SWFDST) (Halcrow Group Ltd., 2010) and a subjective assessment carried out by the Met Office Chief Forecaster in collaboration with the EA regional flood teams and public weather service civil contingency advisors, using a decision support flowchart as well as complementary data. The SWFDST is an Excel-based look-up tool which empirically estimates a SWF risk weighted score (low, medium or high) at the county and unitary authority level, based upon four inputs (FFC, 2011b; Cole *et al.*, 2013; Lane, 2013):

(1) Extreme rainfall probability: maximum probability of set rainfall thresholds being exceeded, estimated based upon UK NWP data, initially at 4 km resolution and in 2013 upgraded to 1.5 km resolution. At first, national average rainfall thresholds for durations of 3 and 6 hours and return periods of 1:30 years (i.e. 40 mm in 1 h and 50 mm in 6 h) were used. However, analyses of recent SWF events revealed that these were often caused by rainfall intensities of less than 1:10 year return period (Hurford *et al.*, 2012). Consequently, in early 2013 the rainfall thresholds used in the SWFDST were extended to durations of 1, 3 and 6 hours and return periods of 1:10 and 1:30 years. The adopted thresholds, rounded to the nearest 5 mm, were, respectively: 20 mm / 1 h, 30 mm / 3 h, and 40 mm / 6 h for return period of 1:10 years, and 30 mm / 1 h, 40 mm / 3 h, and 50 mm / 6 h for return period of 1:30 years (Lane, 2013).

(2) Rainfall spatial extent: this variable provides an indication of the type of meteorological hazard and its potential impact (e.g. localised (convective) vs. widespread storm).

(3) County / unitary area average Soil Moisture Deficit (SMD) value: this variable is imported from the Met Office Surface Exchange Scheme (MOSES) (Cox *et al.*, 1999) and is updated every time the SWFDST is run. If the SMD value is less than 6 mm, the county or unitary area is considered wet and an SMD score of 100 % is assigned. For SMD values greater than 6 mm, the SMD score decreases inversely (score = 6 mm / SMD (mm)). This variable was only incorporated into the SWFDST in 2013 (Lane, 2013).

(4) Blue squares percentage per county or unitary authority: this variable is used as proxy for urbanisation and potential impacts of flooding on the ground. A 1 km resolution map is available for England with blue squares indicating where at least 200 people, 20 businesses or 1 critical service might be flooded to a depth of 0.3 m by a 1 in 200 year rainfall event, according to the EA's Flood Map for Surface Water (EA, 2010, 2012b). It is worth noting that, although new surface water flood risk maps were recently produced and published by the EA (2013), these are not yet being used within the SWFDST.

The weightings used in the SWFDST are derived through calibration based upon data from historical SWF events. Since its launch in 2011, the SWFDST has been continuously updated (as described above) and re-calibrated as more rainfall and flood impact data have become available. Furthermore, as part of the FFC's efforts to streamline its products, the new SWFRA was incorporated into the Flood Guidance Statement (FGS) which is issued daily to Category 1 and 2 emergency responders and provides an assessment of the risk of all types of natural flooding (including SWF) at county level over the next 5 days (FFC, 2011a).

The 2nd generation SWFRA constitutes a step forward; however, it also has a number of drawbacks, including the lack of actual flood velocity and extent estimation and the coarse spatial resolution at which SWF risk is estimated, which is insufficient given the localised nature of this type of flooding.

In order to improve these aspects and in the framework of the Natural Hazards Partnership (NHP, 2013), the FFC is working in collaboration with the Centre for Ecology & Hydrology (CEH) to exploit the surface water runoff generation component of the Grid-to-Grid (G2G) distributed hydrological model of England and Wales (Moore *et al.*, 2006) which uses spatial datasets of terrain, soil/geology and land-cover properties in its configuration. As such, the G2G surface runoff is not only responsive to spatial variation of rainfall input but also to antecedent wetness, urban-cover and terrain slope (and thus seen as an advance on SWFDST). The G2G model is already used operationally for fluvial flood forecasting across England, Wales and Scotland (Cranston *et al.*, 2012; Price *et al.*, 2012), and its surface water runoff component is now output for use in helping prepare the FGS. A pilot project for SWF forecasting over Scotland has used the G2G model configured over Glasgow in support of the Glasgow 2014 Commonwealth Games (Ghimire *et al.*, 2013; SFFS, 2013; Moore et al., 2015). This trial has provided encouraging feedback from the resilience and responder community on its value (Speight *et al.*, 2014). Extending system coverage to other parts of Scotland is in planning. The implementation of the G2G model for the FFC to provide probabilistic SWF hazard footprints and impacts over England and Wales has the potential to be a significant improvement in SWF forecasting and warning. However, the FFC will essentially remain a national service; the aim of meeting detailed local requirements concerning small urban catchments, where SWF is a major concern, may therefore be challenging to pursue without the support of local initiatives.

On balance, it is clear that rapid progress has been made in improving the management and prediction of SWF since 2007. However, there are still a number of technical, social and management challenges that need to be overcome in order to effectively forecast, warn and respond to SWF. The purpose of this paper is to examine the experiences of LAs with the 1st generation ERAs and 2nd generation SWFRA alerts, identify their needs and preferences and explore options and constraints for improving the current warnings and making best use of them. This is done based on survey responses from LAs and on the outcomes of workshops comprising a range of professionals involved in flood forecasting, warning and management. While there may be data quality inadequacies and the survey and workshop outputs are somewhat opinion-based, the results provide useful insights regarding the current status and options for improved SWF warnings in England.

SOURCES AND METHODS

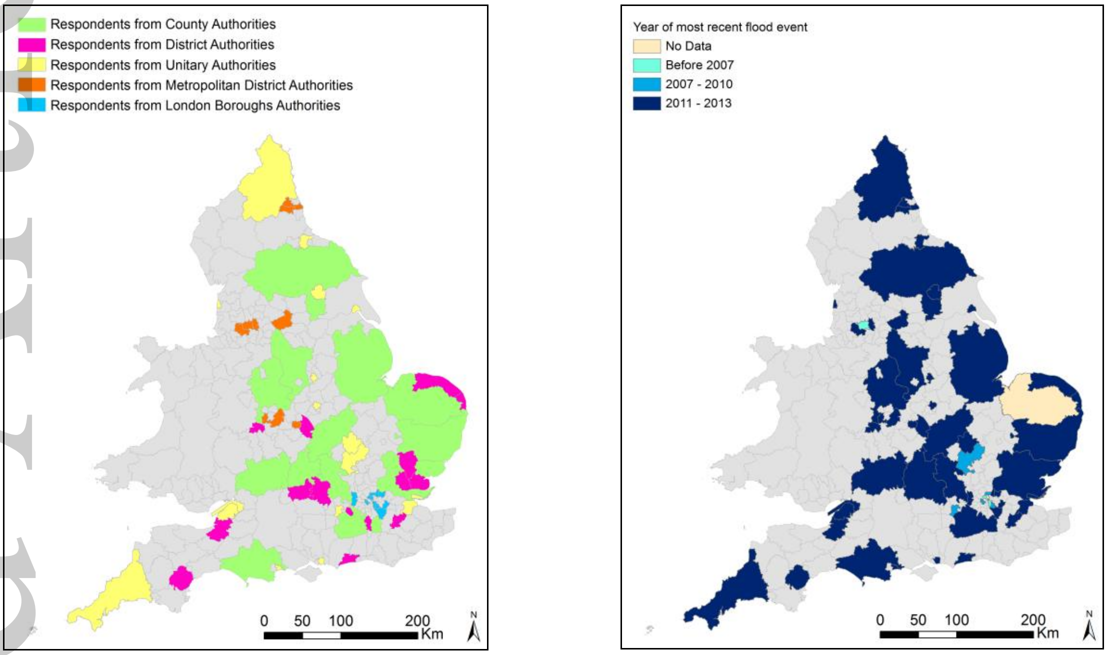
This paper draws upon two main sources of information to gather feedback on the usefulness of, and experiences with, the 1st generation ERAs and 2nd generation SWFRA alerts and the alternatives for improving them given current monetary, human and technical resources:

1. An online survey was undertaken between April and October 2013 targeted at flood risk managers, emergency officers and highways and drainage engineers from county and district authorities in England, who are the main users of the FFC's SWF warnings. It was distributed using SurveyMonkey®'s mailing system to a total of 490 recipients drawn from a LA database owned by the Local Government Information Unit (LGiU, 2014), as well as from the Emergency Planning Advisers Group of the Local Government Association (LGA, 2013). The survey questionnaire comprised 16 questions split into three sections. The first section aimed at obtaining information about the respondent's organisation and his/her role in it, and about the importance and characteristics of SWF within their local area. The second section included questions designed to reveal the usefulness of the ERAs and SWFRA provided by the FFC as well as the respondents' perception and understanding of these services. The information collected in this section constitutes an update and expansion of the work undertaken by Parker *et al.* (2011), which focused on examining the experiences of responders to the 1st generation ERAs, before the 2nd generation SWFRA alerts were launched. The third section was intended to assess the potential response of LAs to more localised SWF warnings in a range of hypothetical scenarios characterised by different levels of certainty and lead times. In order to standardise responses, and given that it was an online survey, most questions had pre-defined answer choices. However, respondents were allowed to include additional comments for each of the questions and many did so. The questionnaire and the raw answers can be found at the RainGain project website: http://www.raingain.eu/en/metadata-research-survey-current-and-future-surface-water-flood-warnings-england
2. Three workshops were held in February 2012, April 2013 and March 2014 with over 40 flood professionals, including specialists, practitioners, academics and local and central government authorities from the UK and EU (workshops minutes and lists of attendees are available on RainGain Project (2014)). During the first workshop, participants were split into three groups according to their expertise and interest: (1) rainfall as an input for SWF modelling and forecasting; (2) hydrological/hydraulic models for SWF modelling and forecasting; and (3) management of SWF. Within each group, experts discussed the current situation, needs and challenges in their specific areas. During the second workshop, rainfall experts, urban drainage modelling experts and flood risk managers were brought together to discuss different ways of improving SWF forecasting and warning systems in England and to identify the main constraints associated with them. During the third workshop, professionals with different backgrounds were again brought together, but this time they were asked to discuss and identify the key factors, including cost and benefits, which would affect a decision to implement and operate a local SWF forecasting system for a city. A set of pre-defined questions was used for guiding the discussion during the three workshops. As will be seen, each workshop built upon the conclusions reached during the previous workshop. Likewise, the design of the survey drew upon the insights gathered from the workshops and the results of the survey fed into the discussions at the last workshop.

RESULTS AND DISCUSSION

Experiences, views and requirements of local authorities with regard to the SWF products provided by the FFC

The results presented in this sub-section are based on the analysis of the survey responses from LAs. A total of seventy four (74) responses were received from district and county authorities from across England (Figure 1a), leading to a response rate of 15 % (74 responses / 490 recipients). Of these, only 57 % (42/74) were complete responses. 40 % of the survey respondents were flood risk and/or water managers, 34 % were emergency planning, resilience and/or business continuity officers, and 26 % were drainage and/or highways engineers. When asked about how big of a concern SWF was in their area of jurisdiction, 66 % of respondents expressed it to be a significant to major concern, 27 % considered it as of medium concern and only 7 % considered it to be a rather low concern. Moreover, 82 % of respondents reported SWF in their area of jurisdiction in the last 3 years (Figure 1b) and all of them were familiar, although to different extents, with the SWF alert services provided by the FFC.



(a) (b)

Figure 1: (a) Location of survey respondents; (b) Year of most recent SWF event in the area of jurisdiction of survey respondents

Local authorities' awareness and understanding of 1st generation ERAs and 2nd generation SWFRA

The survey contained 4 questions designed to reveal the LAs' awareness and understanding of the 1st generation ERAs and 2nd generation SWFRA provided by the FFC. The results are summarised in Figure 2. It can be seen that, in general, LAs have a basic understanding of these services, but do not understand the rationale behind them, nor the differences between the two products in depth. Only a few respondents (16 %) 'strongly agreed' with the statement regarding their understanding of the services provided by the FFC, and none of them expressed full certainty regarding the understanding of the differences between the ERA and the SWFRA. In addition, the percentage of participants who were unaware of the change from ERAs to SWFRA (18 %) and who indicated that they did not understand the differences between the two products (44 %) is concerning. As would be expected, respondents in the emergency planning category appear to have a significantly better understanding of the services provided by the FFC, as compared to flood risk / water managers and highway and drainage engineers: 100 % of emergency planners expressed having a general understanding of the FFC's services, as compared to 80 % of flood risk managers and drainage engineers. Moreover, 71 % of emergency planners indicated that they understand the difference between the ERAs and SWFRA, while this figure dropped to 50 % for flood risk managers and 36 % for drainage engineers.

Additional comments provided by respondents suggest that the general feeling is that they wish to have more information about the services provided by the FFC, especially about the way in which forecasted rainfall is translated into potential flooding and impacts in their area. Examples of comments provided by respondents are the following:

"A key issue we have is that some parts of the organisation don't understand the difference between likelihood and potential impacts. I don't know if this could be incorporated into the five day maps at the top of the statements in a graphical way?"

"So long as the probability of likelihood and impact are properly interpreted then the guidance is useful. The problem is that the probability is not sufficiently emphasised and so there is a tendency for some responders to over react and then we get the problem of seeming to be "crying wolf" too frequently."

The FFC aims to ensure that its partners, including local government, have access to the best possible information. To help it meet this aspiration, the FFC should consider working to further raise user awareness of its services by providing easy-to-understand background information, especially about the 2nd generation SWFRA.

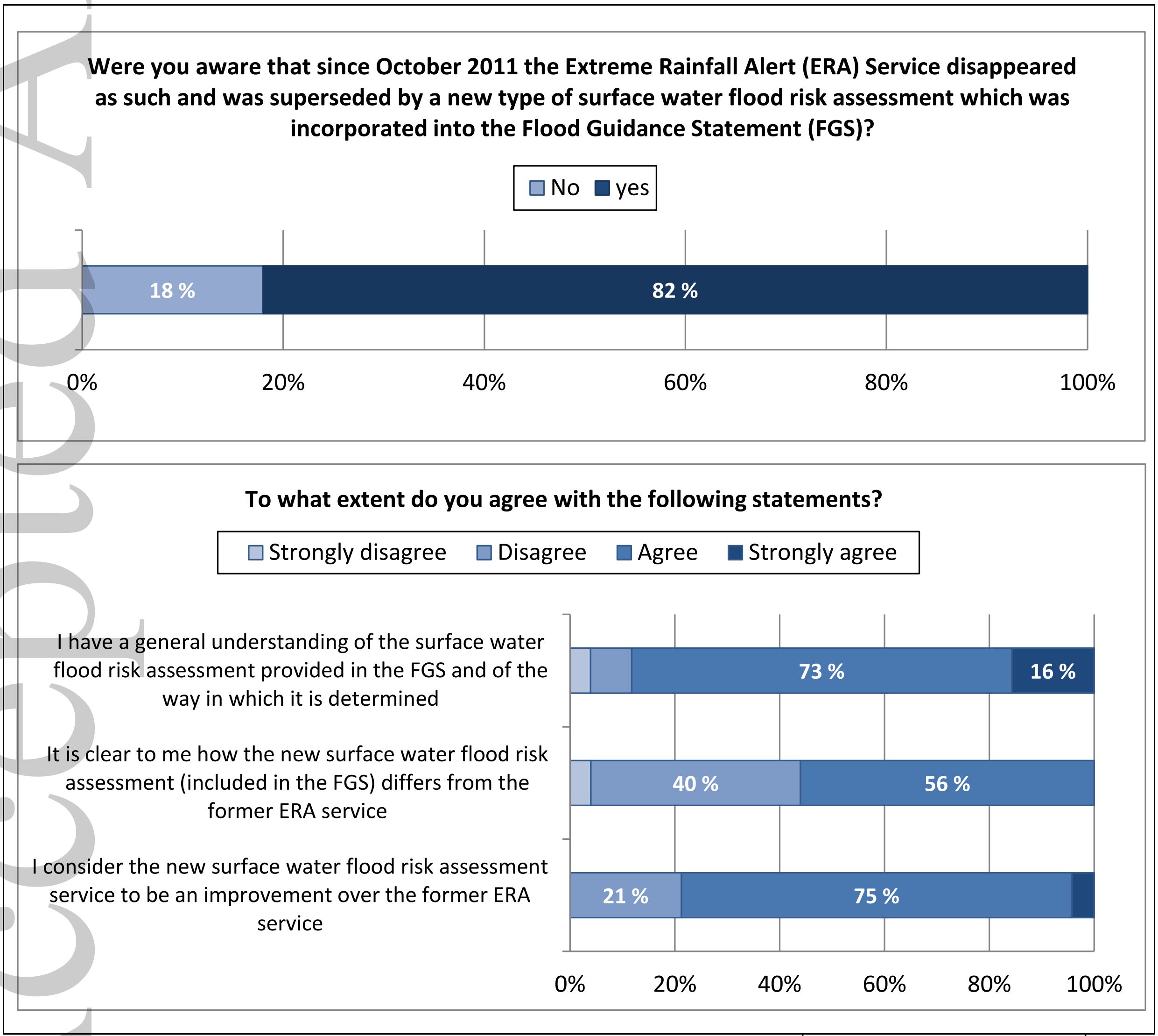


Figure 2: Local authorities' awareness and understanding of the 1st generation ERAs and 2nd generation SWFRA provided by the FFC

Usefulness and limitations of the SWF products provided by the FFC

Almost all survey respondents (98 %) consider the current SWFRA provided by the FFC to be useful for their organisation (Figure 3). The common feeling is that, in spite of being too broad and often uncertain, the SWFRA does provide an overview of the potential risk and helps them to prepare for flooding. The main challenge for LAs is dealing with localised flooding, which, according to respondents, is happening with increasing frequency. Another limiting factor of the current SWFRA is the short lead time frequently associated to high risk notifications. The following comments from survey respondents reflect their general opinion in this regard:

"We have been able to understand the potential for an impact on the ground based on the warnings. We understand that for key risk areas when we are likely to see an impact on the ground. This is harder for the more isolated and local issues, but it helps us to prepare for flooding."

"It's too broad ranging but does provide an overview."

"Still much uncertainty around when and where."

Regarding the response to SWFRA, the decision to implement actions varies according to the risk level. Approximately 89 % of participants indicated that their organisation usually takes action upon receipt of **high risk** of SWFRA notice while only 25 % usually take action upon receipt of **low risk** SWFRA notice (Figure 4). The type of action implemented also varies according to the level of risk. Low-cost precautionary measures, such as monitoring of critical areas, are usually taken upon receipt of SWFRA of any level while more costly measures such as cleansing of gullies are only implemented upon receipt of medium or high SWFRA notice. The most expensive and demanding options, such as placement of staff and resources on stand-by, notification of the general public and road closures, are only implemented upon receipt of high SWFRA. The response to SWFRA alerts also varies according to the lead time (this topic is further discussed in the following section) and depending on whether the notification is received during working hours or not. Moreover, some respondents indicated that, before taking action, they complement the information received from the FFC with other sources including the EA's Flood Advisory Service, current river levels, telemetry data from screens and other critical areas, ground saturation conditions and several general weather forecasting websites.

Participants were also asked about their response to the former ERAs (Figure 4). Although these answers may entail high uncertainty, as participants may not have clear recollections of the service, it can be observed that, in general, LAs are more reactive to the new SWFRA than they were to the former ERAs. This is certainly a positive development which can be attributed to a number of factors, including increased confidence in, and better understanding of, the service provided by the FFC (see Figure 2), improved awareness and understanding of SWF risk in their local area and the creation of standard procedures for reacting to these notifications. In this regard, some participants commented the following:

"This is mostly a matter of my memory. However I have more confidence in the FGS than I had in the ERA."

"The change is in part due to greater clarity in our flood response plans rather than necessarily a reflection on the alerts themselves."

"Joined up document is far better, it is a lot easier to use and reference, which suits many of my colleagues."

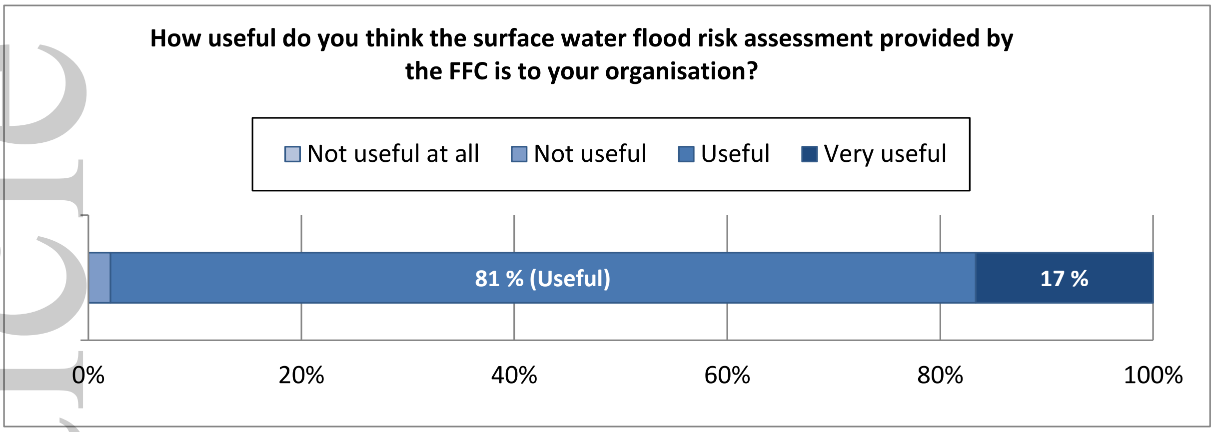


Figure 3: Usefulness of the SWFRA service to local authorities

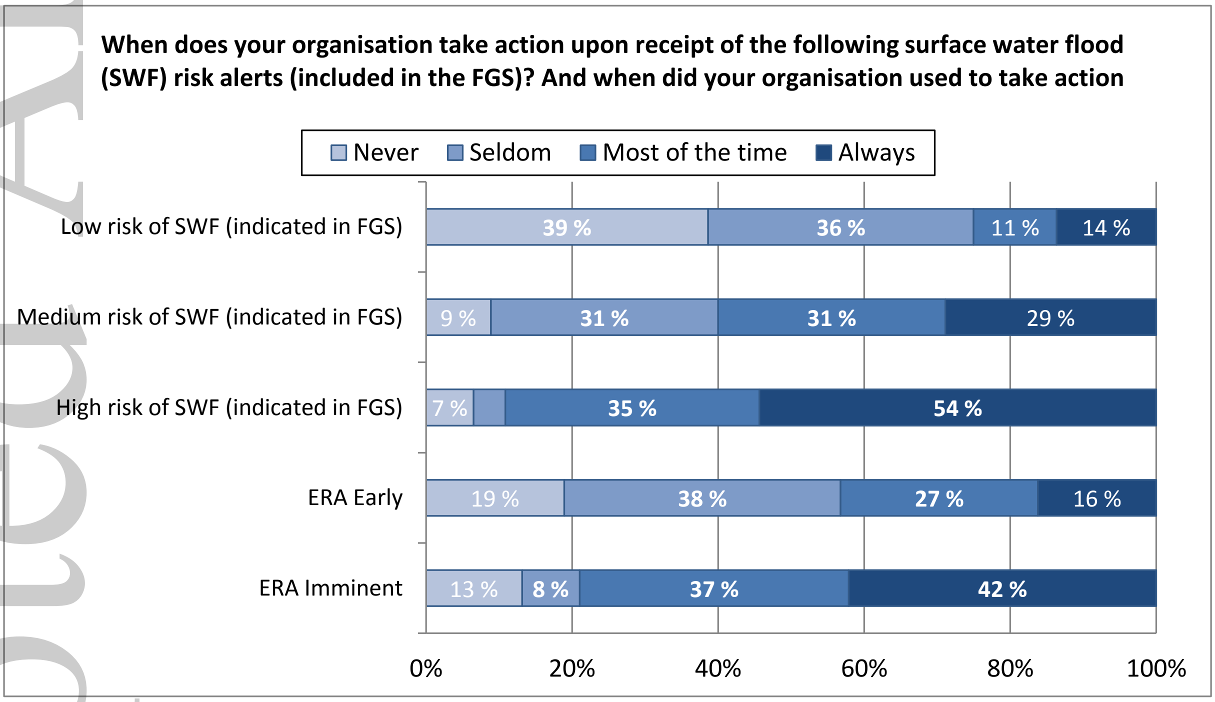


Figure 4: Response of local authorities to current SWFRA and former ERAs of different levels.

Potential response of local authorities to more localised SWF warnings of different probability of occurrence and lead time

Survey participants were asked to indicate which actions (out of a list of pre-defined actions) they would implement if more localised SWF warnings of different probability of occurrence and with different lead times were available. The results are summarised in Table 1. The combinations of probability of occurrence and lead time were based on current knowledge (see for example Golding (2009); Liguori *et al.* (2012)), given the fact that the confidence levels of SWF prediction increase significantly closer to the rainfall event. Notwithstanding the hypothetical nature of this question, the answers given by survey participants provide the following general insights about the perception and tolerance of LAs to probability of occurrence and warning lead time, and about the actions that they can currently implement in order to respond to SWF:

- 20 % probability of occurrence seems to be deemed too low and not warranting the implementation of costly actions. At this level of confidence, fewer than one quarter of LAs (21 %) would monitor gullies, trash screens and other critical areas (A2 in Table 1) and approximately one tenth (10 %) would notify partners and contractors to send an alert (A4). Some respondents mentioned that they can monitor critical areas by means of telemetry and, therefore, the cost of responding in this way is very low.

- 40 % probability appears to be the threshold at which LAs would be willing to start implementing more actions. At this probability level, more LAs would be willing to actively monitor, clean gullies and screens (A2-3) and even place resources on stand-by (A8).

- The actions most sensitive to the probability of occurrence of a flood event are the notification of the general public (A7), the placement of resources on stand-by (A8), the closure of road and areas at highest risk (A10), and the placement of flood defences (A9). The notification of the general public only when confidence levels are high (60-80 % probability of occurrence) is in agreement with previous studies (Parker *et al.*, 2011; Priest *et al.*, 2011; EA, 2012a).

- Lead times as short as 30 min (with high certainty) would enable responders to implement actions that could help in reducing the risk of flooding. 42 % of respondents indicated that they would notify the general public (A7), 64 % would place resources in stand-by (A8) and 24 % would activate control elements (A5) upon receipt of more localised high probability warnings with only 30 min lead time.

- The top 3 combinations of probability and lead time at which the greatest response would be possible are 60 % probability - 2 h lead time, 80 % probability – 1 h lead time, and 80% probability – 0.5 h lead time.

- Resources such as control elements (A5) for preventing flooding and flood warden schemes (A6) are not currently available to most local authorities. While implementing control elements may require high investment and expertise, low-cost training provided by flood warden schemes could help to significantly improve community response to flood risk.

Table 1: Potential response of local authorities to localised SWF warnings of different probability of occurrence and lead time

Lead time - Probability	Potential Actions										
	A1	**A2**	**A3**	**A4**	**A5**	**A6**	**A7**	**A8**	**A9**	**A10**	**A11**
12h - 20% prob.	69%	21%	7%	10%	0%	0%	0%	7%	0%	0%	0%
12h - 40% prob.	21%	47%	24%	26%	0%	12%	18%	32%	0%	0%	0%
6h - 20% prob.	55%	31%	10%	14%	0%	7%	0%	17%	0%	0%	0%
6h - 40% prob.	9%	52%	24%	33%	3%	15%	24%	42%	0%	3%	0%
2h - 40% prob.	13%	53%	23%	33%	7%	13%	23%	50%	3%	3%	0%
2h - 60% prob.	**3%**	**48%**	**36%**	**45%**	**12%**	**30%**	**36%**	**64%**	**6%**	**9%**	**0%**
1h - 40% prob.	9%	44%	28%	31%	6%	16%	28%	53%	3%	3%	0%
1h - 60% prob.	3%	41%	32%	47%	18%	32%	32%	62%	6%	6%	0%
1h - 80% prob.	**3%**	**45%**	**36%**	**48%**	**24%**	**33%**	**42%**	**70%**	**15%**	**18%**	**9%**
0.5h - 60% prob.	3%	41%	28%	44%	19%	34%	31%	56%	6%	13%	3%
0.5h - 80% prob.	**3%**	**45%**	**33%**	**48%**	**24%**	**33%**	**42%**	**64%**	**15%**	**24%**	**15%**

A1: do nothing; **A2:** Monitoring of watercourses, gullies, trash screens and the like; **A3:** Cleansing of gullies and screens in high risk areas; **A4:** Notification of contractors and partners; **A5:** Activation of control elements (e.g. pumps, storage); **A6:** Notification of flood wardens; **A7:** Notification of the general public; **A8:** Placement of staff and resources on stand-by; **A9:** Deployment of temporary flood defences; **A10:** Road closures; **A11:** Closure of public locations susceptible to pluvial flooding (e.g. underground passages).

Analysis of alternatives for improving the current SWF forecasting and warning systems

As indicated in the previous section, the main drawback of the SWFRA currently provided by the FFC is that it is too broad (i.e. county level) and therefore of insufficient spatial resolution given the localised nature of SWF. Another shortcoming mentioned by respondents is the uncertainty associated with the warnings; this derives from uncertainties in the rainfall/weather forecast as well as from the methodology used to translate rainfall into actual SWF impacts, which at the moment is not local enough. Although the FFC is working on the implementation of the G2G model and on the use of improved impact maps in order to improve the quality and spatial resolution of the SWF forecast, the service provided by the FFC will continue to be a national service and as such it is improbable that it can deal with the fine detail of urban catchments (including sewer system and its dynamic interactions with the surface) which are the ones at highest risk of SWF. Alternatives for overcoming this problem and fulfilling the needs of local authorities were discussed during the workshops held in February 2012, April 2013 and March 2014. Through these workshops answers to the following questions were sought, whereby it should be noted that, given the wide variety of professional and academic backgrounds of workshop participants, the questions analysed during the workshops were kept simple so as to avoid confusion and allow meaningful discussions.

- **Which general approach would be more appropriate for implementing localised surface water flood forecasting and warning systems in England: (a) a single national service or (b) a two-tier (national/local service)?**

  Participants were of the view that a two-tier approach was most suitable, with a main rainfall and broad flood forecasting and warning service at the national level provided by the FFC, and local systems, especially for "hotspots", operated by LAs in collaboration with the EA. This conclusion is in agreement with the outcome of a series of workshops conducted by the EA in 2012 (see EA (2012a)). At present, the technical skills and expertise do not exist locally and LAs are facing budgetary cuts which make the implementation and effective use of these systems ever more challenging. These constraints and alternatives for overcoming them are next discussed.

- **What type of forecasting system (technically speaking) would be most appropriate for local areas in England, considering the users' requirements and resources currently available? What are the constraints for implementing and making effective use of such a system?**

  As starting point for discussion, the following classification of real-time urban pluvial flood forecasting systems, proposed by Henonin *et al.* (2013), was adopted as it was considered to be of an appropriate level of complexity for workshop participants.

  (a) Empirical scenarios-based system: flood forecast system with no hydraulic model involved in any part of the process. Warning thresholds correspond mainly to forecasted rainfall thresholds and may include other variables that exacerbate SWF occurrence and impacts (e.g. antecedent precipitation and soil moisture, leaf fall, water levels at critical locations, potential impacts). Warning thresholds are defined based on historical flood events and/or knowledge of the local area. This system is similar to the ERAs and SWFRA provided by the FFC, with the difference that warning thresholds would be determined for each local area.

(b) **Pre-simulated scenarios-based system:** flood forecast system with scenario and results catalogue built from previous hydraulic simulations and associated impact estimates (e.g. data driven models trained with results from hydraulic models). The complexity and quality of this system will depend on the type and quality of the hydraulic model and of the rainfall inputs used to generate the flood scenarios. The implementation of a system of this type may be costly; however, the operational cost is rather low and does not require highly-skilled staff. This system is similar to the G2G and impact library approach being pursued by the FFC under the NHP initiative and implemented in the Glasgow Pilot by the Scottish Flood Forecasting Service.

(c) **Real-time simulations-based system:** flood forecast system with real-time hydraulic models and impact estimation. The type of model that is used in this system must comply with real-time forecast standards such as short computational time and fast display of results, while retaining acceptable accuracy. Both the implementation and operation of this type of system are costly and require highly-skilled staff.

In all types of systems the rainfall forecast will most likely come from the Met Office or the joint FFC. Moreover, all systems would benefit from telemetry data (e.g. of water levels and/or flows at critical locations, of condition of elements such as screens) which could be incorporated as a variable of the system.

From a **technical** point of view, workshop participants concluded that all three types of forecasting could be implemented with the technology that is currently available. Model runtimes could still be of some concern for a type 'c' system (Ghimire *et al.*, 2013), especially if surface flows are to be simulated and if ensemble forecasts are to be carried out. However, this issue could be dealt with through hybridisation of urban flood models (i.e. using higher model complexity and resolution for critical areas and lower for non-critical ones) (e.g. Simões *et al.* (2011), Chen *et al.* (2012)) and by making use of modern technologies such as graphic processing units (GPU) and parallel computing (e.g. Lamb *et al.* (2009), Neal *et al.* (2010), Smith *et al.* (2013)). The major technical difficulty identified by participants was the high uncertainty associated with currently available rainfall forecasts, which would dominate the overall uncertainty of the flood forecast, regardless of the type of forecasting system that is used. Efforts should therefore be concentrated on improving the accuracy of rainfall estimates and forecasts, while bearing in mind the limits of predictability and finding a balance between costs and benefits.

Concerning **monetary** resources, it was felt that that the budget available to LAs for flood risk management would be sufficient for implementing and operating type 'a' and 'b' systems, but not 'c' as its operational costs are very high given the cost of software licences and of skilled staff able to operate the system. A common constraint for the implementation of any of the three forecasting systems is the currently high costs of accessing radar rainfall estimates and forecasts by 'new to radar' stakeholders, such as LAs. Partnership working and establishing of cost sharing arrangements would be necessary, should local SWF forecasting systems be implemented.

With regard to the **skills required** for operating and effectively using a local forecasting and warning system, workshop participants felt that, in general, LAs do not yet have the capacity for it. As such, starting with a simple system would be prudent and efforts should be made to gradually build capacity.

Overall, a type 'b' system was seen as a good compromise between cost, benefits and practical delivery. This system could build upon the modelling results and impact data gathered through the Surface Water Management Plans developed in the last few years for most counties and unitary authorities in England (Defra, 2010), as well as upon the new EA

SWF risk maps (EA, 2013). The development of such a system could be outsourced to consultants or local universities and cost savings and synergies could be achieved by working in partnership with neighbouring LAs, water companies, the EA and the FFC. Moreover, participants concluded that implementing telemetry monitoring systems would be a 'quick win' as this would significantly enhance the quality of any forecasting system that is implemented while at the same time collecting data for future model calibration and verification. Another important aspect highlighted by participants, and which remains a major challenge, is awareness raising and engagement of community members in local flood risk management. Community ownership is at the heart of any future service and low awareness would limit the use of improved SWF warnings. Significant efforts are being made in this direction and should continue.

CONCLUSIONS

Following extensive surface water flooding (SWF) in England in summer 2007, rapid progress has been made in improving the forecasting, warning and management of this type of flooding. This paper presents an overview of the progress made in this direction, which includes the implementation of the 1st generation ERAs and the 2nd generation SWFRA. Moreover, through survey responses from local authorities (LAs) and the outcome of workshops with a range of flood professionals, the paper examines the understanding, benefits, limitations, and ways to improve the current SWF warning service. In general, the warning services are perceived as useful by district and county LAs, although their understanding of the rationale behind these alerts, including the difference between likelihood and risk, is low. The majority of LAs do take action upon receipt of the SWFRA alerts, with the type of response varying according to the risk level and lead time (the top 3 combinations of probability and lead time at which the greatest response would be possible are 60 % probability - 2 h lead time, 80 % probability – 1 h lead time, and 80% probability – 0.5 h lead time). Moreover, the LAs' reactiveness appears to have increased over the years and as a result of the 2nd generation alerts superseding the 1st generation ones. This is a positive and encouraging development towards increased resilience to SWF. The main drawback of the current SWF forecasting and warning service is its broad spatial resolution which is insufficient given the localised nature of this type of flooding. Flood professionals believe that, despite improvements, the service provided by the FFC will continue to be a national service and it is unlikely that it can ever deal with the fine detail of some local areas, particularly complex urban areas. Therefore, a two-tier national-local approach is considered more appropriate for generating localised SWF forecasts and warnings for hotspot areas. In this case, a main meteorological and broad flood forecasting and warning service at the national level would be provided by the FFC, and local forecasting and warning systems (which would get input from the national service) would be operated by LAs in collaboration with the EA. Considering current monetary, human and technological resources, a pre-simulated scenario-based system was deemed to be more appropriate in the short term for generating local SWF forecasts and warnings. Cost savings and synergies for the implementation and operation of these systems could be achieved by working in partnership with neighbouring LAs, water companies and the EA. Existing constraints for the implementation of any local forecasting and warning system that require action, include the insufficient accuracy of currently available rainfall estimates and forecasts, the lack of capacity at LAs and the low-levels of public flood risk awareness.

While the present study focused on a single area (i.e. England), the review, findings and recommendations presented herein provide useful insights for other areas around the world, particularly urban areas, in which heavy rainfall induced flooding (commonly referred to as surface water flooding and pluvial flooding) is also a major – and fast growing – concern (Jonkman, 2005; Borga *et al.*, 2011). Although a lot of research has been carried out in recent years aiming at improving the modelling, forecasting and warning of this type of flooding, operational SWF warnings are still rare (Parker *et al.*, 2011; Priest *et al.*, 2011; Henonin *et al.*, 2013; Sene, 2013). The system that is currently in place in the UK is one of the first of its kind. By presenting the experiences made by its users with its implementation, this paper provides a useful source of information for other countries tackling a similar problem.

ACKNOWLEDGEMENTS

The authors would like to acknowledge the support of the European Union's Interreg IVB NWE Programme to the RainGain project, of which this research is part. Thanks are also due to Dr. Andy Lane and Jon Millard from the FFC who provided details of the surface water flood warnings, and to lead local flood authorities, academics, consultants and other professionals who took part in the survey and workshops conducted as part of this study.

REFERENCES

Borga, M., Anagnostou, E. N., Blöschl, G. & Creutin, J. D. (2011). Flash flood forecasting, warning and risk management: the HYDRATE project. *Environmental Science & Policy,* **14** (7), 834-844.

Chen, A. S., Evans, B., Djordjević, S. & Savić, D. A. (2012). Multi-layered coarse grid modelling in 2D urban flood simulations. *Journal of Hydrology,* **470-471**, 1-11.

Cole, S. J., Moore, R. J., Aldridge, T., Lane, A. & Laeger, S. (2013). Rreal-Time hazard impact modelling of surface water flooding: Some UK developments. In *International Conference on Flood Resilience: Experiences in Asia and Europe*, Exeter, UK.

Cox, P. M., Betts, R. A., Bunton, C. B., Essery, R., Rowntree, P. R. & Smith, J. (1999). The impact of new land surface physics on the GCM simulation of climate and climate sensitivity. *Climate Dynamics,* **15** (Article), 183-203.

Cranston, M., Maxey, R., Tavendale, A., Buchanan, P., Motion, A., Cole, S. J., Robson, A., Moore, R. J. & Minett, A. (2012). Countrywide flood forecasting in Scotland: challenges for hydrometeorological model uncertainty and prediction. In Proceedings of *Weather Radar and Hydrology*. IAHS, Exeter, UK.

Defra. (2010). *Surface Water Management Plan Technical Guidance*. Department for Environment, Food and Rural Affairs, London, UK. Available online: http://www.defra.gov.uk/publications/files/pb13546-swmp-guidance-100319.pdf [accessed 05.09.2012].

Environment Agency (EA). (2010). *What is the Flood Map for Surface Water - Operational Instruction 538_10*. Environment Agency, Bristol, UK.

Environment Agency (EA). (2012a). *Surface Water Flood Warning - June 2012 Workshop Summary*. Environment Agency, Bristol, UK.

Environment Agency (EA). (2012b). *What do the flooding from surface water maps show and how were they created?* Environment Agency. Available online: http://www.environment-agency.gov.uk/research/planning/129324.aspx

Environment Agency (EA). (2013). *What is the updated Flood Map for Surface Water?* Environment Agency, Bristol, UK.

Environment Agency (EA). (2015). *Risk of flooding from surface water*. Environment Agency. Available online: http://watermaps.environment-agency.gov.uk/wiyby/wiyby.aspx?topic=ufmfsw#x=357683&y=355134&scale=2

Flood Forecasting Centre (FFC). (2010). *Extreme Rainfall Alert - User Guide*. Flood Forecasting Centre, Exeter, UK. Available online: http://www.ffc-environment-agency.metoffice.gov.uk/media/pdf/FFC_ERA_User_Guide.pdf [accessed 21.05.2013].

Flood Forecasting Centre (FFC). (2011a). *Flood Guidance Statement - User Guide*. Flood Forecasting Centre, Exeter, UK. Available online: http://www.ffc-environment-agency.metoffice.gov.uk/services/FGS_User_Guide.pdf [accessed 21.04.2014].

Flood Forecasting Centre (FFC). (2011b). *How the FFC assesses surface water flood risk - Internal Briefing*. Flood Forecasting Centre, Exeter, UK.

Ghimire, S., Dunn, S., Golding, B. W., Pierce, C. P., Roberts, N. M., Moore, R. J., Cole, S. J. & Speight, L. (2013). *Surface water flood forecasting for urban communities: A Review*. CREW - The James Hutton Institute, Aberdeen, UK.
Golding, B. W. (2009). Long lead time flood warnings: reality or fantasy? *Meteorological Applications,* **16** (1), 3-12.
Halcrow Group Ltd. (2010). *Developing alerting criteria for surface water flooding (Report NA096)*. Environment Agency, UK.
Henonin, J., Russo, B., Mark, O. & Gourbesville, P. (2013). Real-time urban flood forecasting and modelling - a state of the art. *Journal of Hydroinformatics,* **15** (3), 717-736.
Hurford, A. P., Priest, S. J., Parker, D. J. & Lumbroso, D. M. (2012). The effectiveness of extreme rainfall alerts in predicting surface water flooding in England and Wales. *International Journal of Climatology,* **32** (11), 1768-1774.
Jonkman, S. N. (2005). Global Perspectives on Loss of Human Life Caused by Floods. *Natural hazards,* **34** (2), 151-175.
Lamb, R., Crossley, M. & Waller, S. (2009). A fast two-dimensional floodplain inundation model. *Proceedings of the Institution of Civil Engineers - Water management,* **162** (6), 363 - 370.
Lane, A. (2013). Surface water flood forecasting and guidance in the UK: theory, performance and outlook. In *Second RainGain National Observers Group (NOG) Meeting*, London.
Local Government Association (LGA). (2013). *Local Government Assciation - Emergency Planning Advisers Group*. Available online: http://www.local.gov.uk/emergency-planning-advisers-group [accessed 29.04.2014].
Local Government Information Unit (LGiU). (2014). *Local Government Information Unit: The local democracy think tank*. Available online: http://www.lgiu.org.uk/ [accessed 29.04.2014].
Liguori, S., Rico-Ramírez, M., Schellart, A. & Saul, A. J. (2012). Using probabilistic radar rainfall nowcasts and NWP forecasts for flow prediction in urban catchments. *Atmospheric Research,* **103**, 80-95.
Moore, R. J., Cole, S. J., Bell, V. A. & Jones, D. A. (2006). Issues in flood forecasting: ungauged basins, extreme floods and uncertainty. In Proceedings of *Frontiers in flood forecasting, 8th Kovacs Colloquium* (pp. 103-122). IAHS, Paris, France.
Moore, R. J., Cole, S. J., Dunn, S., Ghimire, S., Golding, B. W., Pierce, C. P., Roberts, N. M. & Speight, L. (2015). *Surface water flood forecasting for urban communities*. CREW - The James Hutton Institute, Aberdeen, UK.
Neal, J. C., Fewtrell, T. J., Bates, P. D. & Wright, N. G. (2010). A comparison of three parallelisation methods for 2D flood inundation models. *Environmental modelling & software,* **25** (4), 398-411.
Natural Hazards Partnership (NHP). (2013). *Natural Hazards Partnership - About Us*. Available online: http://www.metoffice.gov.uk/nhp/about-us [accessed 29.04.2014].
Parker, D. J., Priest, S. J. & McCarthy, S. S. (2011). Surface water flood warnings requirements and potential in England and Wales. *Applied Geography,* **31** (3), 891-900.
Pitt, M. (2008). *The Pitt Review: Learning lessons from the 2007 floods*. Cabinet Office, London, UK.
Price, D., Hudson, K., Boyce, G., Schellekens, J., Moore, R. J., Clark, P., Harrison, T., Connolly, E. & Pilling, C. (2012). *Operational use of a grid-based model for flood forecasting*. Available online: http://www.icevirtuallibrary.com/content/article/10.1680/wama.2012.165.2.65
Priest, S. J., Parker, D. J., Hurford, A. P., Walker, J. & Evans, K. (2011). Assessing options for the development of surface water flood warning in England and Wales. *Journal of Environmental Management,* **92** (12), 3038-3048.
RainGain Project. (2014). *RainGain UK National Observers Group Meetings*. Available online: http://www.raingain.eu/en/uk-observers-group-meetings [accessed 29.04.2014].
Sene, K. (2013). *Flash Floods: Forecasting and Warning*. Springer, Dordrecht.
SFFS. (2013). *Surface water flood alerting: project update*. Scottish Flood Forecasting Service. Available online: http://floodforecastingservice.net/page/2/ [accessed 29.04.2014].
Simões, N., Ochoa-Rodríguez, S., Leitão, J. P., Pina, R., Sá Marquez, A. & Maksimović, Č. (2011). Urban drainage models for flood forecasting: 1D/1D, 1D/2D and hybrid models. In *12th International Conference on Urban Drainage*, Porto Alegre, Brazil.
Smith, L. S., Liang, Q. & Quinn, P. F. (2013). A flexible hydrodynamic modelling framework for GPUs and CPUs: Application to the Carlisle 2005 floods. In *International Conference on Flood Resilience: Experiences in Asia and Europe*, Exeter, UK.

Speight, L., Cranston, M., Moore, R. J., Cole, S. J., Golding, B., Pierce, C., Wright, B., Roberts, N., Ghimire, S. & Dunn, S. (2014). Development of a pilot surface water alerting tool for Glasgow and operational use during the Commonwealth Games. In *12th British Hydrological Society National Symposium*, Birmingham, UK.

UK Parliament. (2004). *Civil Contingencies Act 2004 - Schedule 1: Category 1 and 2 Responders*. Available online: http://www.legislation.gov.uk/ukpga/2004/36/schedule/1 [accessed 14.05.2013].

UK Parliament. (2010a). *Flood and Water Management Act 2010*. UK Legislation

UK Parliament. (2010b). *Reducing flood risk*. Available online: http://www.parliament.uk/business/publications/research/key-issues-for-the-new-parliament/green-growth/reducing-flood-risk/ [accessed 13.05.2013].