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Risk communication in emergency response to a simulated extreme flood

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Abstract

Risk communication in flood incident management can be improved through developing hydrometeorological and engineering models used as tools for communicating risk between scientists and emergency management professionals. A range of such models and tools was evaluated by participating flood emergency managers during a 4-day, real-time simulation of an extreme event in the Thamesmead area in the Thames estuary close to London, England. Emergency managers have different communication needs and value new tools differently, but the indications are that a range of new tools could be beneficial in flood incident management. Provided they are communicated large model uncertainties are not necessarily unwelcome among flood emergency managers. Even so they are cautious about sharing the ownership of weather and flood modelling uncertainties.

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1. Introduction

More than £200 billion worth of property and infrastructure, and over 4 million people, are at risk from flooding around Britain's rivers and coasts and in towns and cities. Flooding in July 2007 demonstrated that when water treatment plants, transportation and power systems are adversely affected, the effects of flooding can reach almost the whole country. The risks of flooding in Britain are predicted to grow to unacceptable levels over the next one hundred years. Annual average flood damages are set to rise significantly (Office of Science and Technology 2004). Increasing risks and flood damage potential need to be addressed across a broad front, including through new flood risk management strategies and reductions in global emissions. Fresh flood risk management strategies are needed for improved catchment-wide and urban flood storage. There is a need for better land use management and tighter floodplain planning controls (Howe and White,

2001; Pottier et al., 2005). Development which is located in floodplains must be made more resistance and resilient. River conveyance needs improving and the flood defence maintenance programme needs speeding up. The effectiveness of flood forecasts and warnings needs to be enhanced (Parker, 2004) alongside more effective emergency planning and response during flood incidents (Penning-Rowell and Wilson, 2006).

Providing a seamless emergency response to flooding was one of the key recommendations of the 'Bye report' (Independent Review Team, 1998) following the infamous Easter 1998 floods in England and Wales. After these floods, the flood forecasting and warning service and the emergency response were roundly criticised. Significant improvements are in train especially in flood modelling and forecasting, in the way in which flood warnings are organised and communicated, and in learning lessons from recent floods. Even so effective flood incident management remains a major challenge. This was demonstrated by the Cumbrian floods around Carlisle in 2005 (Government Office for the North West, 2005) during which power and communications broke down, and also by the July 2007

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Flood incident management

Principal activities	Elaboration	Principal agencies involved	Regulatory basis and key standards relating directly to floods
Preparedness for floods	Awareness raising; training; rehearsals; documentation; contingency plans	Met.Office; EA; LA; police, fire service; other emergency services; hospitals; media	
Providing flood information and communicating flood risks	Awareness raising; publicity campaigns; website information; flood fairs	EA	Civil Contingencies Act 2004 incident management roles and responsibilities of EA and professional partners
Detecting flooding	Instrumentation; monitoring, data collection and analysis	Met. Office; EA	Ministerial Directive 1996 giving EA the lead role in flood warning dissemination
Forecasting flooding	Utilising data; flood modelling; forecasting events	EA	Flood warning codes and levels of service adopted by EA
Disseminating flood warnings	Communicating warnings to professional partners and the public; media management	EA	Incident response standards adopted by EA for flood risk management
Promoting effective warning response	Awareness raising; promoting inter-agency cooperation and working; acquiring response	All agencies and professional partners and voluntary bodies	
Public security and search and rescue	Securing any related crime scene; ensuring public are safe	Police; fire service; EA	
Effective after care	Looking after evacuees; transport; rest centres; rehabilitation	LA, voluntary services	

EA – Environment Agency; LA – Local Authority

Fig. 1. Outline of UK flood incident management organisational activities and responsibilities.

floods in the lower Severn valley in which the demountable flood defences for the town of Tewkesbury failed to arrive in time because of flooded and congested roads.

Flood incident management comprises preparedness for floods; providing flood information; communicating the risks of flooding to raise public awareness; detecting and forecasting floods; communicating flood warnings to the public and to professional partners; promoting effective warning response and responses to flooding; effective emergency exercises and planning; co-operation between emergency services; media management and effective aftercare (Fig. 1). In England and Wales the principal professional actors involved in flood incident management are the Meteorological Office, the Environment Agency, local authorities, the police, the emergency services (e.g. fire, ambulance and voluntary services), and the media.

It is vital that communication tools optimise the risk communication exchanges occurring at each professional interface given the inevitable anxiety and stress of a time-constrained emergency. This paper reports the results of an exercise designed to investigate the value of meteorological, hydrological and engineering models used as communication tools provided by scientists for professionals working in the River Thames estuary in London. These professionals must make decisions about how to respond to flood warnings. The exercise also sought to identify the need for improvements to flood forecasting tools through the trialling and assessment of their value to professional stakeholders. International research on warning commu-

nications (e.g. Drabek, 1999, 2000; *Emergency Management Australia*, 1999) has highlighted the issue of the use of technical, non-transparent language in communications between flood forecasters and those responsible for issuing flood warnings both to the general public (e.g. Smith et al., 1990; Hiroi, 1998, Parker, 2004) and to its professional partners, such as the emergency response organisations (Rosenthal and Bezuyen, 2000). Faulkner et al. (in press) identify significant translational discourse issues surrounding the risk communications between scientists and professional users of flood risk information, including in the flood warning arena. The Environment Agency has recently established an agenda for research into incident management (Environment Agency and DEFRA, 2006). The agenda clearly identifies communication across 'external interfaces' as a key component, although it does not make explicit the need for 'fuller' translations of science into dialogue and communications which might be available and appropriate to the professional recipients.

Scientific developments in modelling weather and flood futures

The development of meteorological, hydrological and engineering tools and models has an important role in improving risk communication during 'real-time' events. A wide range of meteorological 'futures' models, flood routing simulations and physically-based rainfall-runoff models is now available at a range of scales. Elsewhere, in

the coastal setting wave surge models are making the ‘pasting’ of wind-driven wave-surge models onto verifiable tidal flood surge models increasingly commonplace.

Forecasting an event at time T for a future at $(T + \delta t)$ is uncertain. Uncertainty of any risk assessment, whether used for flood warnings or floodplain inundation risk maps, rests not only with the science but also with other considerations, such as the scientist’s own technically-informed judgments or predictions. Uncertainties about both model structures as well as how they become propagated (or ‘ramped’) has been the concern of several recent papers (Bevan, 2005; Pappenberger et al., 2005). The use of ‘ensembles’ as a way of mapping futures from the updated Bayesian models used by the Meteorological Office has vastly increased the articulation of the uncertainty of the predictions. In ensemble modelling, a sample of possible model futures, starting from time T , is mapped or articulated in graphical form for $(T + \delta t)$. A ‘control’ simulation, which represents the best estimate of the initial conditions after data assimilation at time T is also run. The other members of the ensemble represent perturbations of the control (and in the case of the weather forecasts, this may also include different resolutions in the numerical solution). A distribution of futures can be produced from the ensemble set, and articulated visually (as maps, for instance, or pressure field distributions). Weather ensembles, used in the workshop simulation introduced below, are not associated with a probability, but represent a range of expert-defined possible futures – in effect, an expert system. Although this suggests an explosion of uncertainties in ‘futures’ modelling of this kind, by iteratively assimilating new constraining data as the event unfolds, the uncertainty does not necessarily expand in such an uncontrolled way as it is ramped through subsequent model runs or components. For instance, Pappenberger et al. (2005) have proposed some ways of dealing with the computational constraints of evaluating the full range of uncertainties (and constraints on uncertainties) in the European Flood Forecasting System flood forecasting project when discharge data are available for data assimilation.

Ensemble modelling developments, and also hydrodynamic modelling developments, lend themselves to potentially visually and easily comprehensible representations. It is possible that over time, risk communication will increasingly embrace these new technologies. Additionally, given effective translation, possibly by some intermediary service, these possibilities may mean that flood warning and emergency response professionals making decisions in constrained time situations can ‘own’ the more sophisticated science of some of the new models and tools.

The Thames estuary workshop and exercise

A risk communication exercise was organised at the Meteorological Office in Exeter, England in March 2006 to trial the sort of risk communication tools that are

Table 1

Research priority areas (RPA’s) in the Flood Risk Management Research Consortium

Research priority area (RPA)	Title of research area
RPA 1	Programme management
RPA 2	Land use management
RPA 3	Real-time forecasting
RPA 4	Infrastructure management
RPA 5	Whole systems modelling
RPA 6	Urban flood management
RPA 7	Stakeholder and policy
RPA 8	Morphology and habitats
RPA 9	Risk and uncertainty

available, or will soon be available, to managers and professionals operating in flood affected areas of the Thames Estuary. The exercise was embedded in a 4-day workshop organised under the auspices of the UK Flood Risk Management Research Consortium (FRMFC) which aimed to help integrate work from a number of Research Priority Areas (RPAs) contributing to the development of flood simulation tools (Table 1).

The Thames estuary and the Thamesmead embayment

The Thames Estuary is a unique navigational waterway and an historic maritime gateway to London (Fig. 2). The Estuary contains the Port of London and is a major focus for industry, commerce, transport and recreation. The Estuary and surrounding land is the setting for national regeneration initiatives associated with the Thames Gateway developments, the London Olympics and offshore wind farms. A high concentration of dwellings is planned: around 120 dwellings per ha compared to a normal level of around 30 dwellings per ha even in Southeast England (Environment Agency Thames Estuary ‘TE2100’ project Lavery and Donovan, 2005).

The principal flood risk in the Thames estuary is presented by tidal surges originating in the North Sea (the Thames and its tributaries also generate fluvial floods). These surges travel up the estuary towards London. During the 1980s the Thames tidal flood exclusion barrier (termed ‘the Barrier’ below) was constructed to provide a 1:1000 year standard of tidal flood protection. The Barrier has flood gates located on the bed of the river. When a tidal event is forecast they are rotated and raised to hold tidal floods at bay. The Barrier, and its associated sets of downstream flood embankments and walls and related smaller moveable barriers (e.g. the Barking Barrier), must therefore be operated on receipt of a flood forecast and warning. This is a vital part of flood incident management in the Estuary.

Thamesmead is a large riverside development in the Thames Estuary (Fig. 2). It comprises high and low rise residential blocks with interconnecting walkways and other

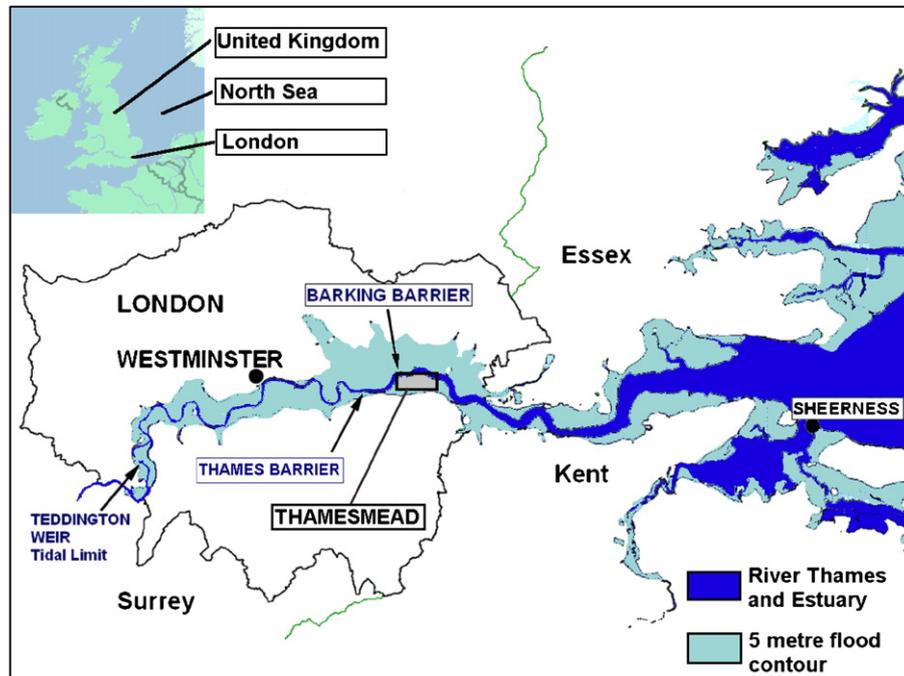


Fig. 2. Schematic indicating the location of the Thamesmead area.

housing that covers 52.6 ha of former marshland the (Erith Marshes). These are east and downstream of the Barrier. Thamesmead was developed in the 1960s by the Greater London Council. It was a long-term solution to London's post-war housing shortage. In order to build on the marshland, five water storage lakes and a number of channels for drainage were incorporated into the design for the town. Also special investigations and techniques were employed to ensure that the land could support the construction, and to raise the properties above the danger of flooding until flood walls along the Thames were raised.

Thamesmead is 5m below the Thames high-tide-defined floodplain, and being downstream of the Barrier its sole protection are the substantial flood embankments. However, under current global warming scenarios, all flood event recurrence probabilities are set to shift in an uncertain way. Generally the standard of protection afforded by the Barrier and flood embankments is expected to markedly decline. Embankment overtopping is set to become a serious issue, and as a result four pumping stations are being constructed. The simulated event described below focussed on the entire section of the Thamesmead embayment shown in Fig. 2 as the area within the box.

Structure of workshop and exercise

The workshop aimed to allow flood modelling teams to use and evaluate new forecasting tools in an unfamiliar event in simulated real-time. Flows were simulated from breach and/or overtopping sites into an inundation model on a GIS base in real-time. The workshop highlighted the sensitivity of the forecasts to the meteorological input using ensembles. The embedded exercise, which is the focus of

this paper, investigated the value of models used as communication tools for flood incident management professionals working in the Thamesmead area. It explored relationships between forecasting, warning and emergency response in the context of the issue of multiple threats; and identified the need for improvements to the forecasting tools by trialling and assessing their value to professionals managing flood risks and emergency response at Thamesmead.

The risk communication exercise focused particularly on the relationship between flood incident management professionals and those scientists developing tools for forecasting and event simulation. We hypothesised that a fuller and broader exchange of information could enhance the handling of the challenges situated between the scientists making predictions and the professionals involved in flood incident management. A number of interrelated issues was considered in the exercise. The first was how the different roles and responsibilities of the professionals affected their communication needs as the simulated event unfolded. Secondly, we focused on the communication tools¹ currently used by professionals, and questioned whether they are optimised to the needs of the particular communication or exchange. Whether or not new communication tools might be helpful to professionals in flood incident management decision-making was explored. Thirdly, we explored where and how the scientific

¹The term 'tool' is used here to mean the formulation of a future which underpins a 'forecast'. This can be in the form of an alert, an event size prediction, or a defence fragility analysis. It might also take the form of a model output in graphical form, or as a map or a real-time visualisation in cross-section or in plan. All these communication tools can include formulations of the uncertainty embedded in that message.

uncertainties are managed in the decision-making process; and whether they are understood and articulated in the decisions made by the professionals. The issue of ownership is important here and so we considered who took ownership of the challenge to deal with the uncertainty in decision-making, including who took ownership of uncertainties which may be disputed between scientist (i.e. modellers) and professional (decision-makers).

Participating in the workshop were modellers from RPA teams (Table 1). The RPA3 team had models of both weather and tidal surge (the physically-based Mesoscale Model 5 or MM5 similar to the Met Office's Proudman Oceanographic Laboratory or POL model). These allow the wind surge to be 'pasted' on top of the tidal surge. This team was also responsible for the modelling and translation of the combined wave dynamic up the Thames towards the Barrier using a MIKE11 model (a widely used dynamic river modelling tool). Representatives from RPA4 developed a fragility and infrastructural model for this wave and tidal effect, concentrating on the Thamesmead embayment. If development of the event allowed, it was proposed that a breach simulated for a subset of ensembles would be used by a modelling team from RPA5 to drive the inundation model across the GIS landscape of the Thamesmead embayment including its streets, parks and residential areas. An essential new part of the available suite of tools was to use ensembles as tools for uncertainty communication by the RPA4 and RPA5 teams. A team from within RPA7 were then expected to test this approach of combining different modelling techniques, in order to assess the utility of differing sorts of tools, as well as their embedded uncertainties. In the first 2 days of the workshop, the modellers generated the predictions, maps and information that they would produce at 3 days (T-72 h) before and 1 day (T-24 h) before a flood event. On the third day they generated forecasts (a 'nowcast') from 6 h prior to the occurrence of an event.

For the input to the surge forecasts, the new experimental Meteorological Office ensemble prediction system was used (Table 2: tools in categories A and B). Real ensemble forecasts were carried out after an event, using archive data, and incorporated into the simulated workshop event as if it were occurring in real-time (tool A5). The surge forecasts are referred to here as 'tools in category C'. In order to simulate the largest possible event, and therefore to test the embankment defence models and tools in category E, the time of the run of the surge model D was adjusted so as to obtain a surge peak as close as possible to high tide. The wave forecasts (Table 2: tools A4 and A5) were those archived at the time of the real event. The simultaneous rainfall forecasts (Table 2: tool B) were obtained using real forecasts, archived at the time of the rainfall event, but moved in real-time to match the high tide. The 1-day and 3-day ensembles were simulated using the capabilities of the STEPSTM forecasting system (Pierce et al., 2004) with estimated uncertainty ranges.

The simulated event

In the simulated event in the Thames estuary, the highest tide for 25 years is simulated to occur at 2pm on Thursday 30 March—thus giving a known time for the pre-event sequence to commence. The data are from two real events in 2005: the tidal surge event occurred in November 2005, and the heavy rain event occurred in June 2005 (GLC, 1967; Wigfall, 1997). Artificiality was introduced as the modellers arranged for the modest tidal surge event to synchronise with an extreme tide, and the group of meteorologists translated a heavy rainfall event from NE France to London. An additional artificiality was that the two events are assumed to occur together.

During the workshop it was discovered that at T-72 the simulations suggested that the selected event (which was based on the highest known events) was insufficiently high to test the flood embankments. The group discussed whether this was likely to be a true representation of such a compound event, and the possibility that the smaller than expected event was an artefact of the surge prediction up the Thames, or a suppressed peak by the software used. In the circumstances, a decision was made to proceed with an event more likely to test the range of models present. Therefore a factor of 4 was added to the surge and the model was re-run on T-24.²

The simulation of the extreme event was in several stages. (Fig. 3) In the initial stage, predominantly, meteorological models were utilised. In the second stage meteorological tools were updated using ensemble models over varying timescales. In the third stage, the wave produced by the North Sea storms event which had been generated by the meteorological models, was ramped on to the high tide predictions to give the Sheerness (Fig. 2) water level predictions that run the hydrodynamic model Mike 11 up towards the Barrier. Output from this model allowed the possibility of a breach and/or overtopping of defences to be explored. In the fourth and final stage, 6 h before the anticipated high tide, the real-time inundation of Thamesmead was simulated from the weakest breach location using a two-dimensional flood inundation model (Table 2). Unfortunately, given the artificial computing constraints at the workshop and the lack of on-line data assimilation for constraining uncertainties during this simulation, uncertainty was not directly addressed by most of the modellers, except in the meteorological models where ensembles were available. Thus it is important to differentiate between what might be possible in real operational forecasting, and the uncertainty work of the simulation exercise.

The risk communication exercise

The focus of the risk communication exercise was the risk communication potential of the interface activities in

²This is therefore an unrealistic scenario within the lifetime of the existing flood protection systems, which was a considerable relief to the stakeholders present.

Table 2
List of model outputs that were trialled as decision-support 'tools' and the professionals response to current usage and perceived usefulness of the tools in their decision making

Code	Descriptive support provided by research team in research priority area (RPA) 7.3	EA	LA	ES	Research priority area (RPA) (&IPR/ trademark information where relevant)
A1	Weather map: UK pressure at 000h, i.e. 72h before predicted high tide	U			RPA3 (Meteorological Office. © Crown Copyright)
A2	Weather 'control' predictions of pressure made 72h before anticipated high tide: UK pressure maps for the ensuing 6, 12, 18 and 24h	U			RPA3 (Meteorological Office. © Crown Copyright)
A3	Weather predictions made 72h before predicted high tide: The 'control' pressure map, alongside 23 ensemble members for the time interval covering the predicted high tide	✓			RPA3 (Meteorological Office. © Crown Copyright)
A4	Weather 'control' predictions of wind speed and direction made 72h before predicted high tide: UK land and wind speed and direction maps for the ensuing 6, 12, 18 and 24h	U			RPA3 (Meteorological Office. © Crown Copyright)
A5	Weather predictions made 72h before predicted high tide: The 'control' windspeed map, alongside the 23 ensemble member maps for the time interval covering the predicted high tide (colour-coded, green to red for increased windspeeds)	U			RPA3. (Meteorological Office. © Crown Copyright)
B1	Rainfall predictions made 72h before predicted high tide: 6 ensemble member maps for the time interval covering the predicted high tide	✓			RPA3 (Meteorological Office. © Crown Copyright)
B2	Rainfall predictions made 72h before predicted high tide: The 'control' rainfall map for the time interval covering the predicted high tide	U	✓		RPA3 (Meteorological Office. © Crown Copyright)
C1	North Sea Surge 'control' predictions of surge height made 72h before predicted high tide: (this is the wind surge in addition to the height of the tide itself) for the ensuing 6, 12, 18 and 24h (colour-coded, green to red for increased surge height)	✓	✓	✓	RPA3 (Meteorological Office. © Crown Copyright)
C2	North Sea Surge 'control' predictions of surge height made 72h before predicted high tide: (this is the wind surge in addition to the height of the tide itself) alongside the 23 ensemble member maps for the time interval covering the predicted high tide (colour-coded, green to red for increased surge height)	✓			RPA3 (Meteorological Office. © Crown Copyright)
D1	Enhanced surge 'control', (high tide plus wind surge from C2), shown in cross-section up to the Thamesmead embankments, (real-time representation using MIKE11)			✓	RPA3 (U. Manchester, MIKE11™)
D2	Plan view of enhanced surge 'control', (high tide plus wind surge from C2), in the Thames estuary area, (real-time representation using MIKE11, colour-coded, green to red for increased surge height)		✓	✓	RPA3 (U. Manchester, MIKE11™)
D3	The anticipated enhanced tide cycle, a selection of ensembles and their exceedance probabilities. The range of ensembles that would overtop the defences at Thamesmead are colour-coded	✓			RPA3 (U. Manchester, MIKE11™)
D4	The breach risks as a bar chart for the anticipated enhanced tidal level, with probabilities associated with both overtopping and breach risk identified on the range of ensemble predictions. (This graph used to select an ensemble member to feed into the breach probability models in E and inundation models F)	✓	✓	✓	RPA3 (U. Manchester, MIKE11™)
E1	Fragility analyses for the Thames embankments around Thamesmead: in plan view with both breach and overtopping probabilities mapped (colour coded for most probable single defence breach—this site used for Models F1 to F4)	✓	✓		RPA4 (CEH Wallingford)
E2	Subset of defence plan information surrounding single most probable defence breach location	✓			RPA4 (CEH Wallingford)
F1	Computer simulation of inundation in the Thamesmead embayment on an OS map background, using data available from E and D4, 24h ahead. Real-time simulation using LIDAR generated DEM	U			RPA5
F2,	As for F1, mapped at different scales, including (F3) detail around the specific breach location	U	✓	✓	RPA5
F3		U	✓	✓	
F4	Depth and velocity plots for any selected point within the Thamesmead embayment, can be shown with depth/velocity plan real-time simulations	U	✓	✓	RPA5

Key: Post-Workshop Questionnaire Survey responses.
EA: environment agency professional; U: currently use in decision making; LA: local authority professional; ✓: do not currently use but would find useful; ES: emergency services professional.

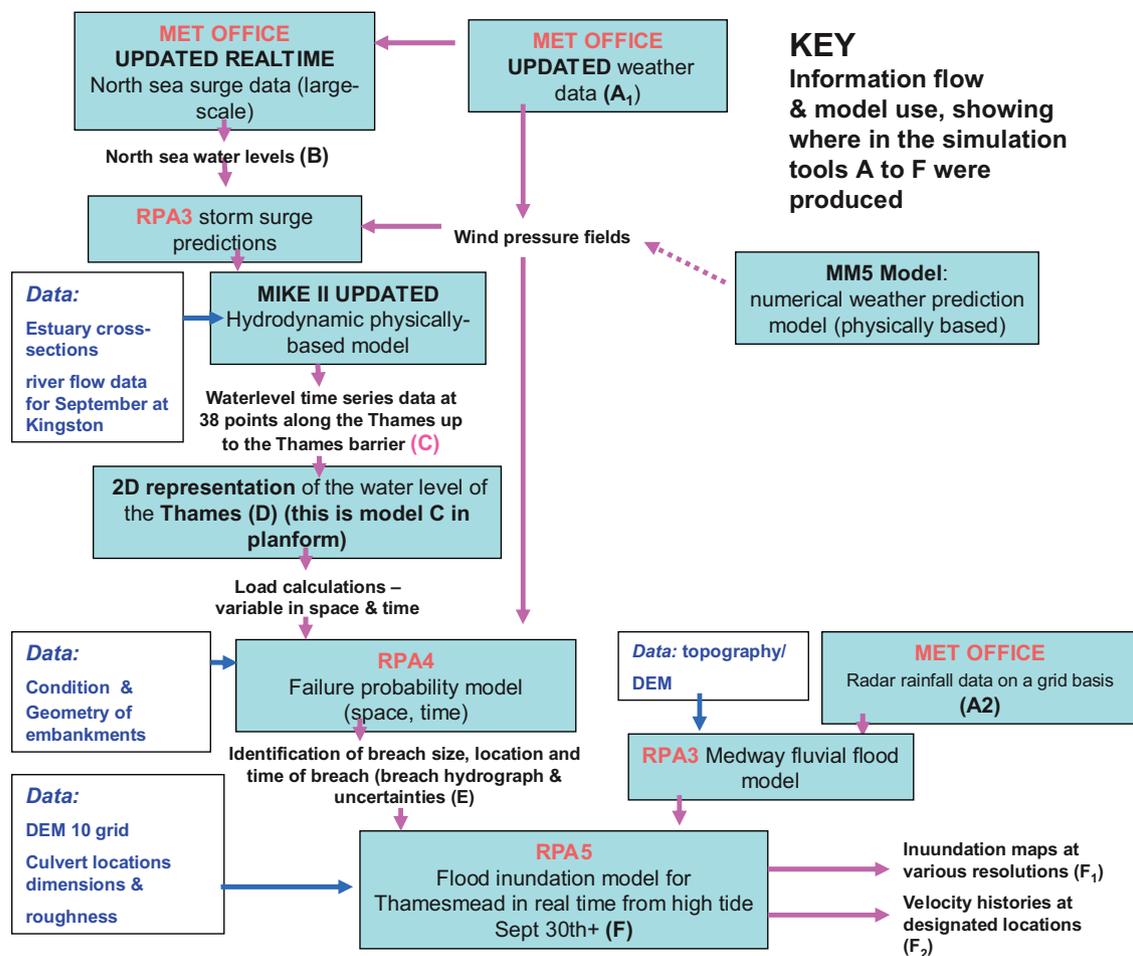


Fig. 3. Information flow and model use during the Exeter workshop.

simulated real-time between the group of meteorological experts, the group of hydraulic engineers, and the group of inundation modellers and their research teams; and a group of flood warning and emergency response professionals working in the area of Thamesmead, London. Four participants (referred to as ‘professionals’) were invited to participate. They were an emergency planning officer for one of the London Boroughs covering Thamesmead, a Metropolitan Police Inspector in a group responsible for emergency procedures and planning in the Metropolitan Police, a senior flood risk manager (the Barrier manager) and a flood incident manager both from the Environment Agency (the flood management agency for England) with responsibilities for the Barrier and for flood warnings affecting Thamesmead, respectively. This group attended the last 2 days of the 4-day workshop. For practical reasons, in this exploratory research, the number of professionals invited was limited, but this small group included representatives of the main agents responsible for acting in flood events (Fig. 1). The simulation provided decision-makers with a long lead time into a possible flood. However, it quickly became clear that professional reaction to forecast information was constrained by organisational responsibilities and abilities. With a simulated sudden

breach of defences the focus of professionals was therefore on refinement of decisions set in pre-planning exercises.

On the first day the four professionals participated in a wide ranging, tape-recorded discussion of their roles and responsibilities in flood incident management. They identified the types of risk communication tools currently used. Risk communication researchers then developed a time line and Power Point presentation to show the outputs, tools and predictions emerging from the modelling processes covering 72 h, 24 h and finally six hours prior to the simulated flood event. The nature of several of the tools that were new to the professional participants, e.g. the ensemble modelling, was ‘translated’ for them as the exercise unfolded. Then, the professionals were invited to report on their experience of the tools and the translation provided, and to evaluate the utility of the new tools and models within their professional setting. On the second day, an overview of all the outputs from the modelling was presented to a plenary session involving all those attending the workshop and exercise with opportunities for questions, explanations and elaborations by the scientists responsible for the modelling. Three of the professionals then gave tape-recorded presentations summarising their reactions and response to the materials generated by the

modellers. A week after the exercise, the professionals were sent copies of the materials listed in Table 2, which with the modelling tools that were developed at the workshop, includes the explanatory descriptions to translate the sense of the models from scientist to professionals. After given time to contemplate away from the workshop, the professionals were asked to complete a structured self-completion postal questionnaire. This included questions on whether and how the materials might be useful to the professionals, and also on the clarity, detail and presentation of uncertainty associated with them.

Results

Current professional roles, responsibilities and communication needs

The professionals reported their existing roles and responsibilities, their current practice in flood risk communication during extreme events, and the tools that are available to them.

The Environment Agency professionals

The role of the Barrier manager is central to risk communication and emergency response in the Thames Estuary area. The Environment Agency professionals from the Barrier reported that the Meteorological Office 'alert' of an extreme event is a key part of Barrier management. Agency professionals understand that the alert is the outcome of a complex Meteorological Office modelling process, professionally interpreted on site, but issued in a shorthand form. The alert is designed to assist the complex decision-making process at the Barrier, including whether or not to close the Barrier and associated defences, and when to close them. Currently, the alert takes the form of three key pieces of data: (1) the estimated water level at a telemetry point; (2) a confidence statement about the model, e.g. 'moderate'; and (3) any error factor added by the Meteorological Office to the model prediction. Together with the level of certainty associated with the prediction, the additional error information (3 above) is crucial for the Agency professionals at the Barrier. This is because it avoids Barrier operators compounding the error with their own estimates of wider decision uncertainty.

Once the alert is issued, assuming that a flood is being generated in the North Sea, Barrier managers also have access to their own science in the form of actual river and sea telemetry, the Agency's North Sea model, and the Meteorological Office's CS3 model.³ The Meteorological Office also provides both routine predictions of cyclical high tides and unusual rainfall events.

It is clear therefore, that the outputs of scientific modelling already inform decisions at the Barrier. However, all of the participating professionals stressed that

decisions are not made on the basis of a single source of information, or in isolation. Depending upon the level of uncertainty in the information (the Barrier professionals described this as "...the degree of residual data in the Barrier models predictions"), and also on the seriousness of the consequences associated with an event, a discussion would occur set around the data available to the Agency and the Meteorological Office. The Barrier duty officer is expected to discuss the data directly with colleagues at the Barrier, and by telephone with the Meteorological Office. Observation and interrogation of the modelling outputs would continue. If technical issues arise with the models, specialist consultants would also be brought into the discussion. This discussion would draw upon any additional data sources, together with the experience and the knowledge of those involved. Although a discussion is undertaken between the professionals, the final decision as to whether action is to be taken, and the form it takes lies with the duty officer at the Barrier. It was reported that a decision to engage the flood defences is taken in the context of the wider financial, social and environmental consequences. As well as risk to life issues, there are the financial costs to businesses associated with disruption to shipping on the Thames, and to road traffic with the closure of roads by engaging the surrounding movable defences. The Barrier manager has to weigh the social, economic and environmental consequences of flood inundation, as these "...outweigh those of operating the defences", including, it seems, operations that turn out to have been inappropriate. The way this was expressed was that there were "...no prizes for not taking action when action was required".

The local authority emergency management and the Metropolitan Police participants

Emergency management decisions, both strategic and tactical, were reported by the local authority and police service professionals to require a balance between the humanitarian issues and issues concerning the limited organisational resources at their disposal and the wider financial consequences of decisions. Each stated that for their organisations, the protection of life was a primary concern, and that scientific data inputs played a role, but were not a central professional concern. Management decisions revolved around availability of staff and material resources and the need to ensure the safety of staff and the public. Concerning Thamesmead, decisions would need to be made about which residents to move first. Given that the local authorities might have to evacuate up to 80,000 people, which is infeasible in a 24 h period, the minimum early warning lead time required can be defined, although confidence in a warning with such a lead time is an issue.

The timing of release of a warning by the Environment Agency is not only dependent upon the Agency's confidence in the data underlying a decision to release a warning. It is also based upon the need for clarity by the recipients. The Agency professionals stated that the decision to release a warning can be viewed as a wider

³POL CS3 is an operational tidal model with a grid resolution of around 12 km. It is two-dimensional providing depth-averaged parameters.

tactical decision, and should be timed, in part, “... *so as not to confuse recipients*”. For example, a formal warning related to, say, an unusual tide may be ‘held’ until 12 h before the event. This is so that recipients of the message are not confused about which tide the warning is associated. However, decisions may be made to provide certain recipients with an earlier warning where it is required for effective action such as evacuation.

Non-coincident communication needs

This discussion above makes it clear that throughout a flood event, such as the simulated or real event, each of the professional organisations have different responsibilities, different associated capabilities, and different timelines for action. These are not necessarily coincident. The Agency professionals at the Barrier are on alert and communicating with the Meteorological Office and their own scientists from an early stage. By contrast, the particular local focus of the local authority emergency management and police services professionals means that their roles are mainly acted out later in the event and are focussed on potentially affected locations. Thus, the differing temporal and spatial focus of each professional’s responsibilities substantially affects their need for communication and the nature of the tools that are likely to be most effective for them.

Response to new flood risk communication tools

The professional’s reactions to the various tools trialled at the workshop are discussed below. The translational descriptions in Table 2 were used to assist the professionals to understand more clearly the model outputs as tools.

Feedback from the Environment Agency professionals

During the exercise it became clear that a number of the communication tools listed in Table 2 were already in use by the Meteorological Office and in the Environment Agency. For the Agency professionals, climate forecasting using the climatic pressure and wind maps (tools A and Fig. 4) and rainfall models (tools B) are commonly available, in the sense that the Meteorological Office Storm Tide Forecasting Service (Meteorological Office STFS) is informed by these tools in order to decide if they should release an alert of an unusual climatic event to the Agency. One and two-dimensional hydrodynamic models (tools D1 and F—see Figs. 5–7) are also available for inundation forecasting in the Agency. The Agency professionals reported that the potential usefulness of these tools had already been illustrated during a threatened flood incident above the Barking Barrier (Fig. 2). The representation of the possible inundation not only helped in emergency planning, but also in effective communication to other professional stakeholders, including the media.

The Agency professionals reported that they would not currently be exposed to the ensemble predictions surrounding the tools (A and B) that inform the final decision of

the Meteorological Office Storm Tide Warning System (STWS). While the decision to operate the Barrier was viewed as a ‘yes’ or ‘no’ decision by the Agency professionals operating the Barrier, they were enthusiastic about embracing some of the uncertainty in the form of ensembles (Fig. 4). Both Agency professionals were eager to discuss how this interface with ensemble modellers might work in practice. The Barrier manager explained: “...*it would be extremely useful to receive ensemble forecasts to assist operational discussion. ... if they (the team) had ensemble forecasts they could have a one-to-one conversation with STWS*”.

In the context of discursive decision-making, it was suggested that the ensembles would need to be available to all parties involved in the discussion at the time (e.g. an interactive conference call was suggested, with the ensembles being available online for both scientist and professional). However, the professionals believed that access to such tools would only be required when decisions were being discussed, rather than tools being available to alert them to events on a daily basis. This is illustrated by the following comment: “...*there is no point in sending those ensembles through for 365 days a year, because what will happen is they’ll get missed, because we’re all human*”.

Feedback on tools from local authority emergency manager and the police representative

All trialled tools were new to the local authority and police professionals. They commented that they were currently dependent upon the ‘experts’ (i.e. from the Meteorological Office and Environment Agency) for the interpretation of the pressure and wind data, and any associated ensembles (tools A and Fig. 4). The weather-based models (tools A and B) and the North Sea surge models (tools C) were of less interest, and viewed as less relevant to their decision-making and response. The police professional considered that the level of detail in the form of scale of tools in categories A and B2 was insufficient to make his organisation’s decisions. However, the local authority professional commented that the rainfall maps (tool B2) could be helpful in discussion of an unfolding event with experts. This interest mainly focused on local authority forward planning and the staff resources required for effective response to an event.

While the surge models (tools C and D and Fig. 5) are not used currently to inform decisions made by the local authority and police professionals, they were considered potentially useful for internal communication of the risk. Working at a finer spatial resolution, that of individual streets, these professionals considered that the defence fragility analyses, breach location predictions and the inundation models (tools E and F, and Figs. 6 and 7), could have greater potential in decision-making about evacuation of people and deployment of resources. Inundation simulations, in particular, could be used to identify ‘hotspots’ for fluvial and urban flooding, other

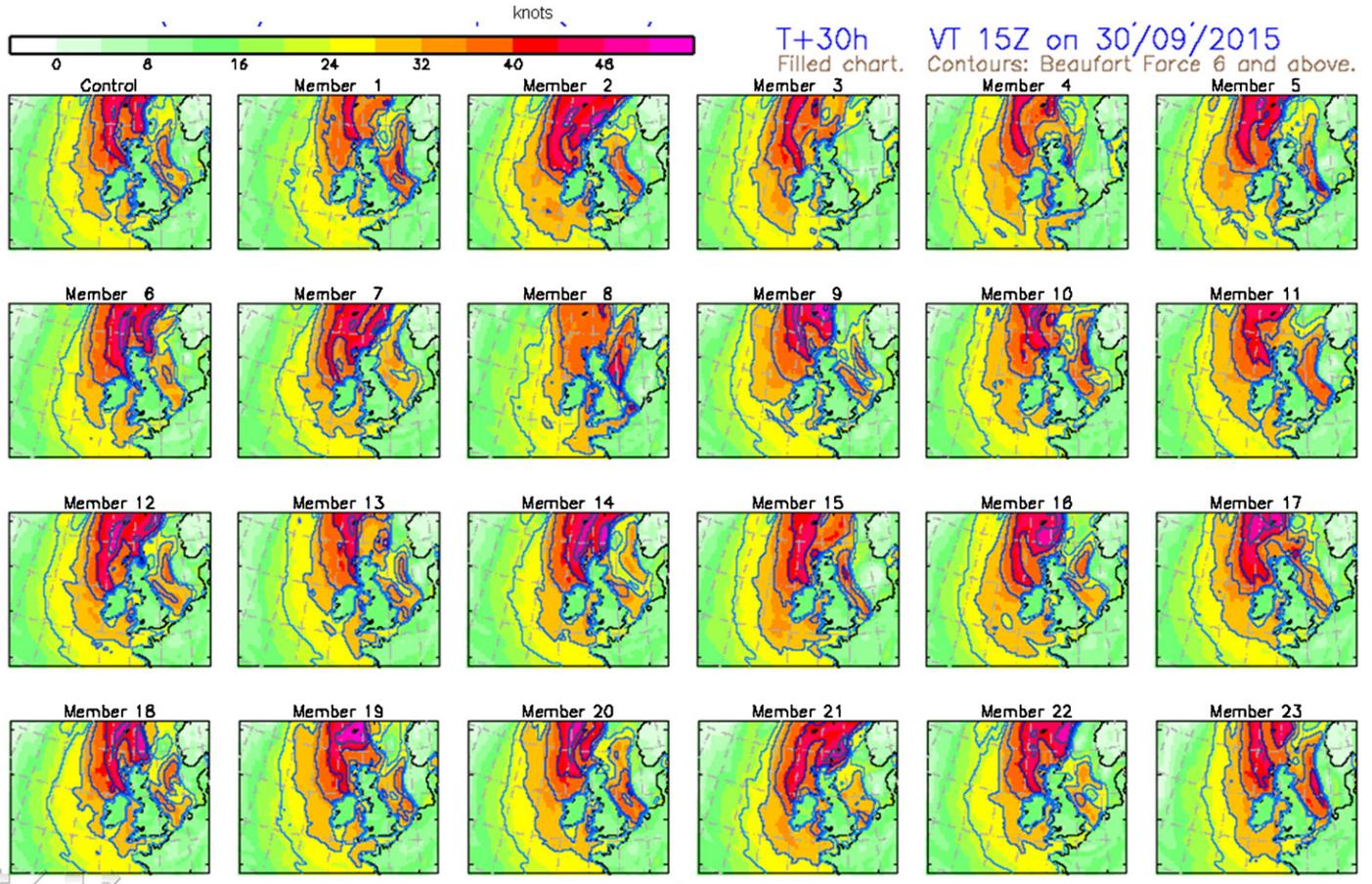


Fig. 4. Tool A5: weather predictions made 72h before predicted high tide: the ‘control’ wind map, alongside 23 ensemble members for the time interval covering the predicted high tide. (Original shaded in colour range from green to red). (c) Crown Copyright.

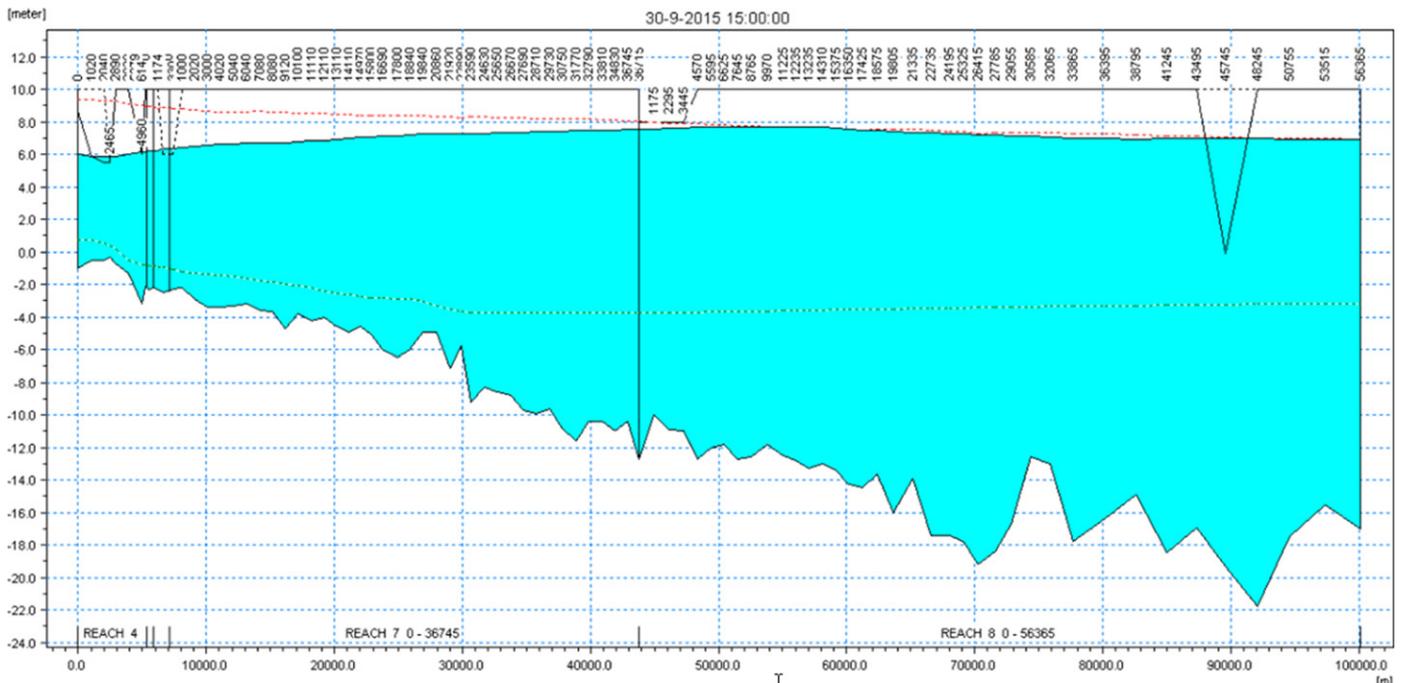


Fig. 5. Tool D1: Enhanced surge ‘control’, (high tide plus wind surge from C2), shown in cross-section up to the Thamesmead embankments (a realtime representation using MIKE11™).

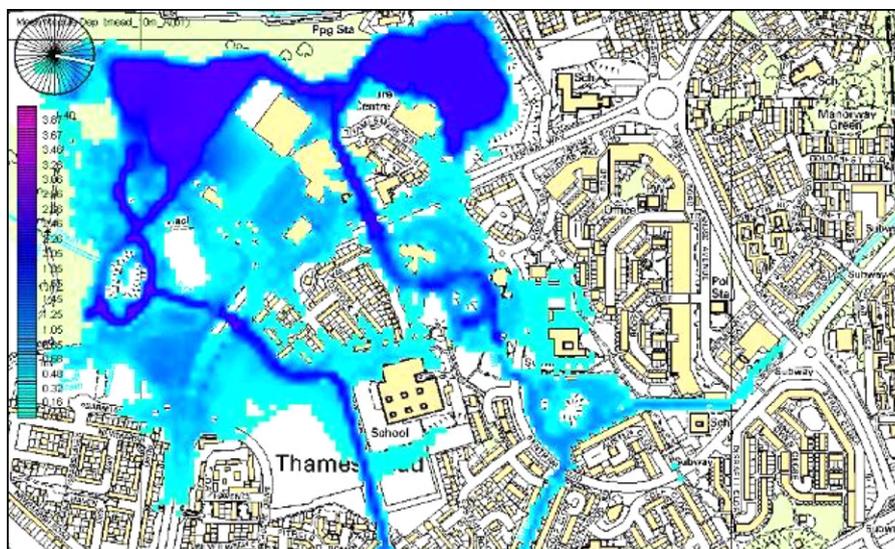


Fig. 6. Tool F3: Computer simulation of inundation of the Thamesmead embayment onto an OS map, using data available from tools E and D4, 24 h ahead of anticipated high tide. Real-time simulation using LiDAR DEM of the embayment, using a two-dimensional hydrodynamic model.

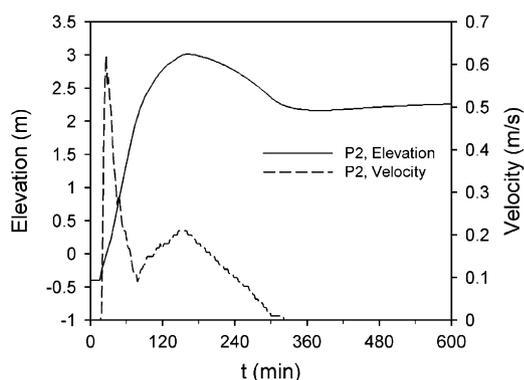


Fig. 7. Tool F4: Depth and velocity plots for any selected point within the Thamesmead embayment. These graphs can be shown alongside depth/velocity plan real-time simulations in plan.

than those already known to the authorities. The local authority professional also considered that the fragility analyses (tool E1) could be useful in decisions regarding evacuation, but for the police service representative their use was limited without further data from the Agency. This latter sentiment was shared by the Agency professional, who stressed that additional information was required in interpretation and release of fragility analyses to Agency professional partners.

For the emergency services, the inundation models (tools F) could help to decide where the police should erect cordons, and also where the fire service should site its large water pumps. This is particularly important for large pumps which, once placed in position, are difficult to move quickly out of harms way. For the local authority professional, the inundation model was perceived as a technical tool which could assist strategic planning. In combination with the more detailed information, the inundation models (tool F3, Fig. 6), were considered very useful for evacuation decisions.

The outputs of flood velocity and depth models (tool F4, Fig. 7) were considered to be potentially useful in informing assessments and decisions about risk, not only to the public, but also to emergency service staff. For local authorities, key issues concern if and when residents need evacuating, to which locations and by what methods. The depth/velocity plots could help in these decisions which might, for example, include decisions about if and how long residents could remain in tower blocks as areas of refuge from flood water.

Both the local authority and police professionals would like more data indicating when flooding would recede, and whether or not there is any likelihood of immediate further flooding. Such information would inform the start of recovery activities which involves decisions about the safety of sending staff back into a flooded area. The models available in the exercise did not directly address these issues.

Ownership of uncertainty

The possibility of an enhanced ownership of a more detailed articulation of the scientific uncertainties was discussed with the group of professionals. It was apparent that for tools currently in use the sharing of uncertainty between different professional roles was grounded in current knowledge and experience of model operating uncertainty and mainly took place in the form of a formal statement in warnings and during decision discussions. It is during discussions that uncertainty can surface and the issue of ownership may be heightened. However, it was apparent that currently ownership is not disputed due to the clear demarcation of who makes the final decision and informal appreciation of who in the discussion has the competency to judge the uncertainty.

In the case of new tools such as the ensembles (e.g., Fig. 5), once explained, the professionals were comfortable with this

new articulation of uncertainty. However, the ensembles were not considered to be tools which the professionals could own and manipulate themselves. A comment directed at the scientists by the emergency management professional was “So basically we can handle the uncertainty, we’re at ease with that, we can handle the ensembles but even at best we probably can’t out do you on that score”. The local authority and police professionals only cautiously accepted the possibility of an enhanced ownership of a more detailed articulation of the uncertainties in the science. Concern was expressed that responsibility for interpretation of (i.e. handling the uncertainties in) all the tools should remain where the expertise lies, and should not overburden other’s decision-making responsibilities. While reluctant to embrace professional ownership of the embedded uncertainty of these models, nevertheless there were several comments about e.g. “... is it accurate?”, because this would be crucial in planning evacuations and deployments generally.

Additional emerging issues

The professionals participating in the workshop and exercise raised a number of views about the trialled communication tools which were additional to the main focus of the exercise.

Improved decision making and anxiety reduction

Clearly, scientific modelling outputs can inform timely emergency decision-making. However, the professionals also believed that ‘science’ can also improve the environment in which decision-making take place. For example, the local authority professional stated that “*the intelligence-led approach is again hugely important, because it enables the decision-makers and the decision-making process to become far more effective and would reduce the panic that will inevitably start to generate both within the public but also the organisation*”. This demonstrates a belief that scientific, evidence-based information can improve decision-making about, e.g., engaging mobile flood defences, and/or evacuating people from a flooded area; and that this in turn is likely to give the public greater confidence thereby reducing their anxiety during an event.

Motivational communication tools

The local authority and police professionals reported that their decisions are based upon interpretation by the experts of “... what won’t, may and will happen”. Forward planning and action in local authority and police departments is dependent upon superiors, and stakeholders such as utility companies, being motivated to take appropriate levels of action in response to an impending flood event. The professionals felt that trialled communication tools could help to persuasively communicate to sceptical audiences the possibility and serious consequences of a flood event. Both the local authority and police profes-

sionals believed that vivid representations, and in particular the animated surge models (tools C1 and D1, Fig. 5) are “*the sort of thing that’s going to make people sit up and really take notice*”.

At the exercise it became clear that the professionals already had a working relationship, either through their responsibilities for the Thamesmead area, or through the collaborative, partnership activities required by the Civil Contingencies Act 2004. The scientific tools trialled during the exercise would be required to operate within the context of these relationships, and of the tools already employed. The police professional commented: “... *I work quite closely with XXX (Environment Agency professional) and if XXX blinks his eyes that tells me everything I need to know ... that is a refinement of lots and lots of trust and communication*” ... Where such working relationships do not exist to the same extent as between the professionals participating in the exercise, the requirements for clarity and the motivational power of the tools to inform becomes more important. This is so for the stakeholders which the professionals have to inform in an emergency, but is to some extent equally an issue for all professionals. This is because the kind of event simulated in the workshop would be very unusual for both the professionals and their organisations.

The meaning of accuracy of information to the participating professionals

The local authority and police professionals commented that they were dependent upon the accuracy of the Environment Agency’s flood warnings. For all three organisations, timely receipt of information was viewed as crucial, but ‘accuracy of information’ was also of considerable concern. For the Barrier professionals, the level of ‘accuracy’ required was the margin of error needed in making decisions to avert major flooding. In the case of the simulated event, the Barrier manager explained that his margin of error was “... *the height of the Barrier and related defences, but as an everyday concern this takes the form of the free-board⁴ on the City side of the Barrier ...*” and that “... *working above this margin of error would be difficult to translate into useful information for decisions*”. This demonstrates that the operational view of ‘accuracy’ and ‘margin of error’ are currently conceptualised very differently from the scientists’ view of model outcomes and uncertainties.

The accuracy of the inundation models, and their ability to deliver detailed information, was also discussed. With their need to make tactical decisions on the ground, the professionals felt that the greater the local detail (e.g. the locations of large pumps) the better. Of some concern was the local authority professional’s view that the finer detail

⁴Free-board is the distance between normal water level and the top of river Thames embanked flood defences. According to the Environment Agency professional this free-board is 45 cm.

implicit in the two-dimensional hydrodynamic inundation models, the greater is the certainty in the predictions suggesting some higher level of 'accuracy' or even 'certainty'. However, if the two-dimensional model is the final output from a complex modelling cascade as trialled at the workshop, inevitably the inundation model is almost entirely dependent on the effectiveness of the models that precede it. This means that the degree of confidence of this apparent detail needs further unpicking to be useful to these professionals. It is clear that the effectiveness of organisations in making strategic and tactical decisions depends to some extent upon the levels of uncertainty associated with the scientific information. If it is to be enhanced ownership of uncertainty must be based upon an improved understanding of the complexity of the science. All parties agreed that they would find uncertainty estimation useful, and that they enjoyed working with the new technologies.

Conclusion

Enhanced inclusion of scientific formulations in the exchanges between the scientists, such as meteorological scientists and flood modellers, and those professionals responsible for managing flood risks, flood defences and the emergency response to flooding is now increasingly possible. Not only is the science of weather and flood prediction advancing, but the science and technology of communications is rapidly developing and expanding. The policy context is also changing with more effective flood incident management being demanded by politicians, the media and the public. This is all occurring during an era in which the possibility of climate-change-induced flooding and greater flood impacts are of considerable concern.

There is a clearly defined requirement for risk communicators in real-time situations to be undertaking effective communication in extreme situations like the simulated event. Equally professionals often demand that flood warnings be clear, unambiguous and as specific as possible, and appropriate to the recipients in language and content. Currently, however, even between scientists and professionals, a simple three or four-point risk warning, or 'alert' (e.g. 'high, medium or low flood risk'), is often issued in one-way mode only (by fax is currently common practice). A note in relation to the scientists' confidence in the certainty of that communication is usually included as a one-line comment. Yet even with the note of caution about prediction confidence, the clarity and brevity of an 'alert' may inadvertently transfer an impression of 'accuracy' which it cannot contain. O'Neill (2004) has argued that from the point of view of the scientist charged with modelling events as they unfold and issuing warnings, emergency incidents can be envisioned to occupy an uncertainty envelope, the size of which reduces as the onset of the event approaches, and the choices become clearer. Scientists are aware that model uncertainties can become 'ramped' in possibly complicated ways. Pappen-

burger et al. (2005) refer to this effect as a 'cascading' rather than a 'ramping' of uncertainties.

In situations such as the defended tidal section of the Thames estuary, where the possibilities include sudden onset of breaches in flood defences, it is clear that these events have some 'lead time' within which the uncertainty of the breach can be evaluated and the options for emergency response assessed. Nevertheless, until the full articulation of scientific uncertainty is possible, in situations when models are assembled in sequence as attempted in the exercise reported here, the inundation model still possesses the power to mislead with the level of apparent predictive capacity it holds. In the case where full articulation of scientific uncertainty was to be implemented, a very important component would have to be visualisation of uncertain forecasts at each stage of modelling. More importantly, continual updating of predictions by on-line observations would need to be available to constrain the uncertainties (as in Pappenburger et al., 2005). The full trialling of uncertainty in communications must therefore wait for development of these models. In this latter respect, we observed that there is currently a stretch between the concept of uncertain science, and the requirement for accuracy reported by the participating professionals. Some translation of language and concepts in this area could be beneficial.

The risk communication exercise demonstrated that greater involvement with models trialled as decision-support tools at earlier stages, as well as improved ownership of prediction in the pre-event period, could be beneficial for flood risk managers including the emergency management professionals. The research indicates that the wider use of a range of new models as communication tools is likely to be valuable. The roles and responsibilities of professionals mean that they have different data communication needs: they therefore value the trialled models differently as communication tools. The Environment Agency professionals were enthusiastic about embracing uncertainty in the form of ensembles, but only during an emerging flood event. The surge models, rather than the weather-based models, were considered to be potentially useful by the local authority and police professionals, but are not currently used by them. Defence fragility analyses, breach location predictions and inundation models were considered to have potential in emergency management decision-making. Similarly, the flood velocity and depth models would be informative in the same context. In some cases, however, data which emergency managers require are not currently available, and this indicates other models which might be produced in future (e.g. a floodwater recession model).

It is not possible to draw firm conclusions that will inform policy from engagement of such a small group of professionals, and from a simulation focused on a single special extreme event. Less experienced flood warning duty officers and those monitoring multiple flood events developing in a number of river catchments might have

different views on the utility of new communication tools such as ‘ensembles’. Nevertheless, our investigation challenges the idea that a large amount of model uncertainty is unwelcome for managers. This paper, therefore, makes a contribution to stimulating the debate about the type and level of new tools to be deployed in flood forecasting, warning and response systems. Viewing certain model outputs as communication tools raises issues of ownership and clarity of uncertainties. Professional participants were cautious about owning or sharing the ownership of model uncertainty. In our view, shared ownership of uncertainty does not negate clear decision pathways or ownership of decisions. Further research is required on these issues, and into the ‘translation’ or explanation required if such scientific outputs are to be communicated.

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