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REAL-TIME HAZARD IMPACT MODELLING OF SURFACE WATER FLOODING: SOME UK DEVELOPMENTS

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ABSTRACT

Following recent UK floods (summer 2007 and Cornwall 2010) and the UK Government's Pitt Review, forecasting and warning of surface water flooding (SWF) has received much attention. To support effective mitigation actions there is a growing demand for more robust, accurate and timely forecast and alert information on surface water flooding and its impacts at local, regional and national scales. The Natural Hazards Partnership (NHP) aims to provide co-ordinated information on natural hazards from across UK government departments, agencies, trading funds and public sector research establishments. Under NHP, a Hazard Impact Model framework is being developed and SWF is one of three initial hazards being trialled. In contrast to rainfall threshold based methods, the NHP prototype SWF approach is based on dynamic gridded surface runoff estimates from the Grid-to-Grid model which is already used for operational fluvial flood forecasting. Methodologies for generating dynamic maps of the possible impact have been derived using national datasets of population, infrastructure, property and transport. The prototype approach is explained and illustrated through a case study along with a perspective on future developments.

KEYWORDS
Forecasting; hazard; impact; Natural Hazards Partnership (NHP); pluvial; surface water flooding.

1. INTRODUCTION

Following the UK floods in summer 2007 and those in Cornwall in 2010, forecasting and warning of surface water flooding has received much attention. Good progress has already been made in response to the UK Government's Pitt Review of the summer 2007 floods (Cabinet Office, 2008). For example, the Extreme Rainfall Alert (ERA) methodology is now embedded within the current Flood Guidance Statement (FGS) services for England & Wales and delivered by the Flood Forecasting Centre (FFC) since April 2009 (FFC, 2010). However, both professional partners and the public now have raised expectations. There is a growing demand for more robust, accurate and timely forecast and alert information on surface water flooding to facilitate effective mitigation actions. In addition to forecasts of the "hazard footprint" (e.g. location and severity) there is also an increasing desire for information on the "impacts" of surface water flooding at local, regional and national scales. Providing an improved countrywide alerting service for surface water flooding is a challenging goal requiring a step-change in capability to come closer to meeting user expectations.

A major driver for the recent developments reported in this paper has come through the Natural Hazards Partnership (NHP). The partnership aims to provide co-ordinated information on natural hazards from across UK government departments, agencies, trading funds and public sector research establishments (including the authors' organisations). In order to deliver more targeted risk assessments and advice to government and Civil Contingency Act Category 1 and 2 responders, a cross-agency Hazard Impact Model (HIM) framework initiative is developing specific impact models.

The three hazards being considered initially are surface water flooding (led by the Centre for Ecology & Hydrology (CEH)), land instability (led by the British Geological Survey) and high wind (led by the Met Office). These hazards are underpinned by an impact and vulnerability cross-cutting work package led by the Health and Safety Laboratory. An ambitious aim of the HIM is to quantify the potential impacts over a given forecast horizon: e.g. How many homes may be affected by surface water flooding? What is the potential disruption on the road network due to the effects of high winds?

2. METHODS

2.1 Surface Water Decision Support Tool

Currently the FFC uses a Surface Water Flooding Decision Support Tool (SWFDST, Halcrow (2011)) along with expert judgement and feedback from local Environment Agency flood teams, public weather service civil contingency advisers and the Met Office chief forecaster to produce the surface water flooding element of the FGS. The tool calculates an empirical flood-impact weighted score for 109 county and unitary authority areas. Initially this score was derived using the probability of forecast rainfall (UK4 – 4km scale Numerical Weather Prediction (NWP) model) exceeding national 30-year return period rainfall thresholds for durations of 3 (40mm, 37.5% weighting) and 6 (50mm, 37.5%) hours along with some assessment of rainfall type (no rainfall, widespread, organised, localised; 25% weighting).

The overall risk category for an area is determined by assessing its susceptibility to surface water flooding based on the percentage of 1km pixels where at least 200 people, 20 non-residential properties or 1 critical service might be flooded to a depth of 0.3m according to the 1 in 200 year Flood Map for Surface Water (FMfSW). The specific weightings set in the tool are derived offline using past case studies and are dependent on the NWP rainfall forecast product used (note this offline calibration is required each time the NWP model changes significantly). During the initial development of the SWFDST, a 30-year return period rainfall threshold was chosen as representative of the design capacity for most urban drainage systems (Hurford, 2012) but it was recognised that rainfalls with return periods of 10 years or less often caused surface water flooding due to a range of factors (Halcrow, 2011). Offline trials using a 10-year return period threshold with the UK4 rainfall resulted in too many alerts being issued: so the conservative 30-year thresholds were used for practicality. Subsequent analysis (Tang et al., 2012) indicates the likely cause to be the UK4 NWP parameterization scheme making convection too vigorous and storm cells too large.

Recent advances in NWP have resulted in the UKV variable resolution model with ~1.5km resolution over the UK mainland. Convection (albeit poorly resolved) is explicitly represented and dynamic convective processes are better captured when compared to UK4 (Tang et al., 2012). Recalibration of the SWFDST tool was undertaken using UKV rainfall and considering additional rainfall thresholds and soil moisture deficit criteria (Halcrow, 2013). Since April 2013, each area score is formed from scores for the *maximum* probability of UKV forecast rainfall exceeding national rainfall thresholds for 1, 3 and 6 hour durations and return periods of 10 (27.8% weighting) and 30 (22.2%) years, the average soil moisture deficit (16.7%) and some assessment of rainfall type (33.3%).

2.2 Prototype Surface Water Flooding Hazard Impact Model

2.2.1 Surface runoff modelling and thresholds

The current decision-support tool approach has proved useful for “first guess” operational guidance. Some known limitations include use of static vulnerability/exposure data, the likelihood is controlled by rainfall alone, only one depth threshold from FMfSW is used and no assessment of flood velocity is made. To address some of these limitations, the NHP initiative is prototyping a coupled hydro-meteorological modelling approach to characterise the surface water flooding hazard footprint in terms of location and severity. A requirement of the approach is that it must have the potential to run nationally and in real-time.

The prototype Surface Water Flooding (SWF) Hazard Impact Model (HIM) is using the Grid-to-Grid (G2G) distributed grid-based rainfall-runoff and routing model developed by CEH (Moore et al., 2006). G2G is already used operationally for countrywide forecasting of fluvial flooding across England, Wales and Scotland by the FFC (Price et al., 2012) and Scottish Flood Forecasting Service (SFFS) (Cranston et al., 2012) to support the fluvial elements of the FGS. It runs at a 15-minute time-step to align with national hydrometric data availability and is currently configured at a 1km resolution. Gridded outputs include estimates of river flow (m^3s^{-1}), surface runoff (average water depth over a grid square in mm) and soil moisture deficit (mm or percentage).

A major driver for developing the area-wide G2G approach was to address the ungauged hydrological forecasting problem and facilitate forecasting “everywhere”. The runoff-production and routing elements of the model use supporting spatial datasets linked to physical-conceptual formulations of the relevant hydrological processes to capture the spatio-temporal evolution of runoff and water flows across the model domain (Moore et al., 2006). Therefore, G2G runoff production is shaped by the storm pattern, spatial datasets on landscape properties (land-cover (e.g. urban/sub-urban), terrain, soil and geology) along with dynamically and spatially changing antecedent soil moisture as calculated through continuous water accounting within G2G. It is anticipated that using dynamic gridded surface runoff estimates from G2G will provide a potentially significant step forward in assessing the surface water hazard footprint, compared to methods primarily based on rainfall depth.

To progress the hydrological modelling approach it has been necessary to move from the national rainfall depth thresholds and consider surface runoff thresholds. The methodology for deriving national rainfall thresholds was to average the Flood Estimation Handbook (FEH) rainfall depth estimates (Faulkner, 1999) for a given duration and return period across 8 major UK urban centres (Hurford, 2012). Here, prototype surface runoff thresholds have been subjectively chosen by analysing accumulated G2G surface runoff estimates during a small range of historical rainfall events and obtaining a reasonable match with any reports of surface water flooding. To allow some flexibility in matching the model with reported events, a “low” and “high” threshold were investigated. The prototype surface runoff thresholds are given in Table 1.

Although the runoff thresholds appear low in percentage terms when compared to the rainfall depth thresholds, they are actually in keeping with national UK pluvial hazard mapping approaches. Such approaches use a FEH (Faulkner, 1999) rainfall depth for a given duration and return period and then make various assumptions to derive the “effective rainfall” for input to detailed mapping models. For rural areas, a simple percentage runoff is typically used (e.g. 55% for Scotland and 39% for England). For urbanised areas a 70% runoff percentage is commonly used together with a 50% summer rainfall storm profile (Faulkner, 1999) and losses due to urban drainage capacity are limited to a specified rate, usually 12 mm h^{-1}. As a reference, Table 1 provides typical urban and rural effective rainfalls for each of the national rainfall return period thresholds. An interesting feature is that, for a given return period, the rainfall depth threshold and rural effective rainfall increase with duration as expected but the urban effective rainfall decreases due to the 12 mm h^{-1} assumption for maximum urban drainage losses. The prototype surface runoff thresholds intuitively increase with increasing duration.

Table 1. National rainfall depth and prototype surface runoff thresholds. Urban effective rainfall assumes 70% percentage runoff, 50% summer storm profile and 12 mm h^{-1} losses to urban drainage. Rural effective rainfall assumes a simple 55% percentage runoff.

Duration	Rainfall depth threshold (mm)		Urban effective rainfall (mm, %)		Rural effective rainfall (mm)		Prototype surface runoff threshold (mm)	
	10yr rp	30yr rp	10yr rp	30yr rp	10yr rp	30yr rp	Low	High
1 h	20	30	5.5, 28%	11.6, 39%	11	16.5	7	8.5
3 h	30	40	4.7, 16%	8.6, 22%	16.5	22	13.5	16
6 h	40	50	3.2, 8%	5.9, 12%	22	27.5	19	23

2.2.2 Hazard impact assessment

HSL have led development of methods to produce novel dynamic maps that summarise the possible impact of surface water flooding. These combine the dynamic hazard footprint with time-varying national impact datasets and build on previous Defra work (project FD2655) that mapped the possible impacts of a 1953 type coastal flooding event. At this prototype stage, two simple types of 1km hazard footprint have been derived: (i) low hazard footprint – pixels where any of the low thresholds have been crossed, (ii) high hazard footprint – pixels where *all* of the high thresholds have been crossed. Initial work has focussed on assessing impacts to population, property and vulnerable locations.

The National Population Database (NPD) was initially developed by HSL (2008) to support the Health and Safety Executive in its statutory duty to manage the risks associated with major hazard industrial sites, and has since been used in a wider context for a variety of applications. It collates information from a range of sources including government datasets and the census, and allows estimations of populations with a spatial context. It includes GIS layers representing different population themes such as Residential, Workplace and Sensitive (categorised into schools, hospitals, care homes, child care locations and prisons), as well as layers representing roads, transport terminals, retail areas and stadia. The NPD layers can be combined to represent various population scenarios including variations with time. It has been used as the base population dataset in this assessment to provide daytime and night-time population estimates aggregated to a 1km resolution grid and the four basic scenarios trialled are listed in Table 2. The definition for vulnerability used for this study is given as "*Over 75 or suffering a long-term limiting illness*" and has been applied using relevant output area statistics from the 2001 Census.

Table 2. Population scenarios using the National Population Database

Population scenario	Definition
General Daytime[1]	*Residential Daytime, Care Homes, Hospitals, Schools, Prisons, Workplaces*
General Night-time	*Residential Night-time, Care Homes, Hospitals, Prisons*
Vulnerable Daytime[1]	*Vulnerable Residential Daytime, Care Homes, Hospitals, Prisons, Schools*
Vulnerable Night-time	*Vulnerable Residential Night-time, Care Homes, Hospitals, Prisons*

[1] Daytime is 09:00-17:00 and residential term-time values are used.

Across England & Wales, the Environment Agency maintain the National Receptor Dataset (NRD) (EA, 2013) which includes a number of layers categorised into themes such as Buildings, Transport, Utilities, Land Use, Agriculture, Heritage and Environment. The buildings theme includes a comprehensive dataset of point locations representing buildings, classified into 10 Bulk Class Descriptions, and 68 Categories. Two main building types were extracted from the buildings theme for the initial analysis: (i) Housing – this uses the Dwellings bulk class description, (ii) Retail – uses the Shop/Store and Retail bulk class descriptions. Road and railway information in the Transport layer has been used to identify transport infrastructure that may be at risk.

3. CASE STUDY RESULTS AND DISCUSSION

A case study event in summer 2011 for north-east England was chosen to illustrate a prototype of the SWF Hazard Impact Model. During 3 August 2011, a sequence of showers passed over eastern parts of England, some becoming extremely intense for short periods. The FFC had identified this event as having significant surface water flooding impacts with York, Corby, Thorne and Goole particularly affected. As typical with sequences of intense localised storms, there was significant spatial variation in rainfall accumulations. Analysis of the 5-min weather radar rainfall data suggests between 40 and 60mm fell over parts of Goole and the south of York and is in keeping with contemporary raingauge data (e.g. Howden, just north of Goole recorded 41.9mm in a 12-hour period).

For this first offline case study, the UK composite radar rainfall data provided by the Met Office was used (forecast rainfalls will be considered in future work). Figure 1 provides an insight into how the modelling approach works and some of its potential advantages. The left hand column presents gridded maps of threshold exceedance for 1-hour accumulations of rainfall (top row) and surface runoff (bottom row) for periods ending 17:00 and 18:00 and shows heavier rainfall in the earlier period. Immediately apparent is that the pattern of runoff threshold exceedance is more localised and targeted compared to that for rainfall at 17:00, whilst there are relatively more areas of runoff exceedance compared to rainfall at 18:00. This highlights the dynamical interactions that the hydrological modelling approach provides and also that the use of land cover datasets in the model formulation has increased runoff in urban areas as expected. To illustrate this further, a pixel near Thorne has been selected for more detailed analysis. The right column of Figure 1 shows time-series of pixel rainfall, G2G surface runoff and G2G soil moisture deficit (SMD). This shows an intuitive sequence of the pixel being relatively "dry" (high SMD) at the start of this summer event and having a low runoff volume and percentage up to 17:00 (runoff threshold not crossed), despite the significant rainfall totals (rainfall threshold crossed). This is followed by a period of lower rainfall up to 18:00 (rainfall threshold not crossed) but high runoff volumes and percentage (runoff threshold crossed) due to saturation of the pixel. Finally SMD slowly recovers and will provide the modelled antecedent SMD for the next rainfall event.

Hazard maps have been produced every hour for the 12-hour period starting 12:00 3 August 2011. Methods are being explored on how to present and summarise the associated impact information. Figure 2 provides a graphical summary that pools the hourly hazard maps over the event period and provides summary impact estimates for each of the contiguous high hazard areas.

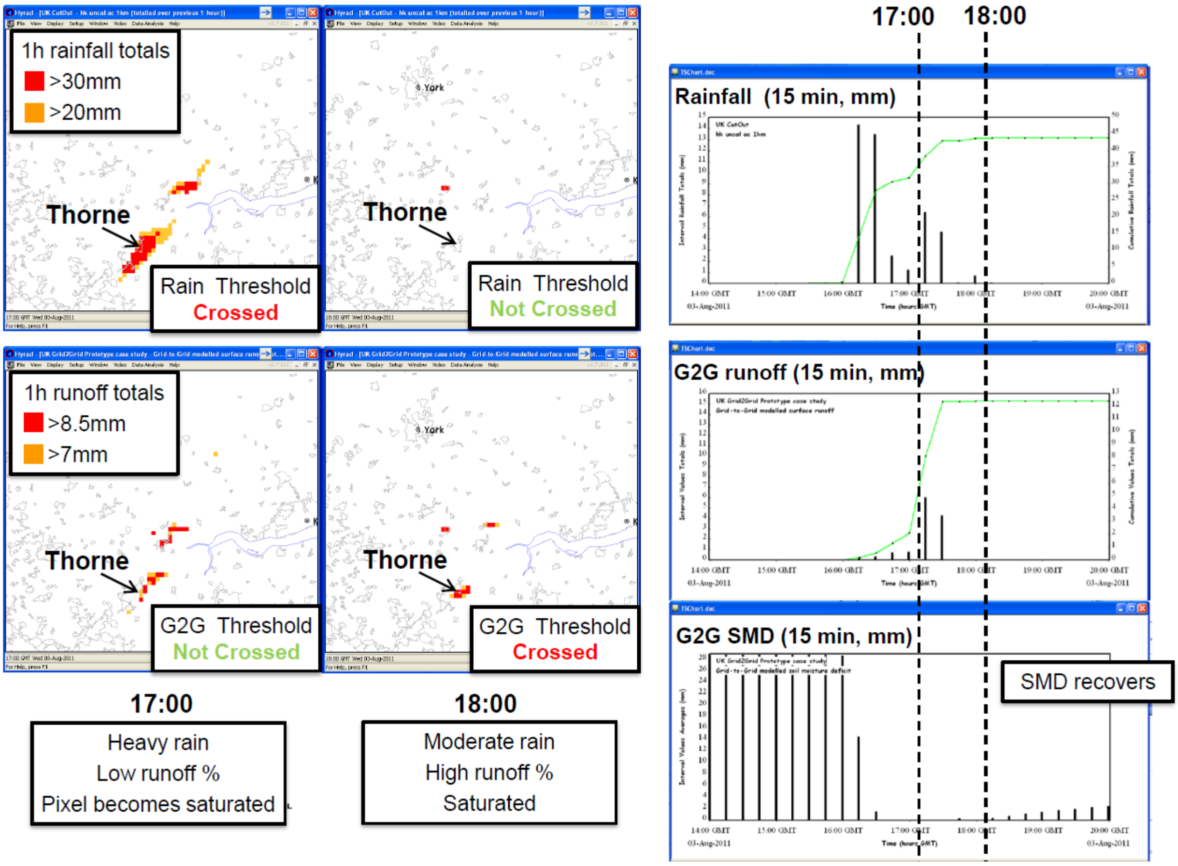

Figure 1. Selected G2G modelling results for 3 August 2011. Left column shows gridded maps of threshold exceedance. Right column gives detailed analysis for the highlighted "Thorne" pixel.

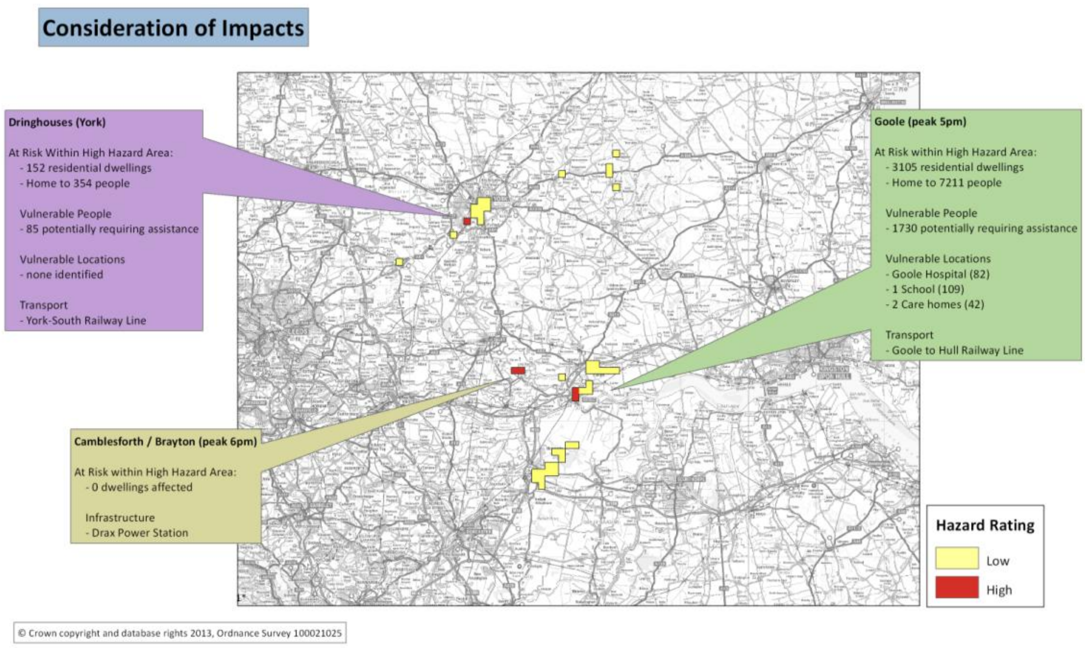

Figure 2. A prototype surface water hazard impact map: Goole and York, 3 August 2011

4. CONCLUSION

There are numerous methods within the literature for defining hazards, their footprints, associated impacts and risk assessments: these form a source of ongoing debate within and beyond the NHP. Although development of the NHP Hazard Impact Model framework is at an early stage, the pragmatic approach taken to provide an end-to-end prototype for SWF shows great potential for the HIM whilst also recognising that individual elements or methodologies can be improved and adapted in the future. The benefits of the NHP in bringing together a wide range of government agencies is also evident with new collaborations between partners (e.g. CEH and HSL) producing novel methodology and products. In the first instance the SWF HIM is planned to be used operationally to support FFC in producing the FGS which is widely used by the emergency response community.

For the SWF HIM in particular, the G2G modelling approach has shown some utility and potential to provide benefits beyond existing rainfall depth threshold approaches. There is a planned programme of future work to (i) investigate strategic G2G model developments to improve surface runoff estimates, (ii) investigate best use of the latest deterministic and ensemble rainfall forecast products, (iii) further develop the SWF HIM products in consultation with relevant stakeholders, (iv) extend the case study and method validation including reference against the FFC's existing decision support tool, and (v) carry out a near operational trial of SWF HIM products within FFC.

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