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Developing an impact library for forecasting surface water flood risk

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Abstract

During surface water flooding events, emergency responders require detailed information on the risks posed in order to provide an appropriate and effective response. Few early warning systems quantitatively estimate the risk and impacts of surface water flooding. Improvements in computational processing capability, availability of new datasets and developments in forecasting models means that the forecasting information currently being supplied by the Flood Forecasting Centre can be improved upon through the application of a timely, impact-based model. This article presents a novel approach to collating receptor datasets into a pre-calculated Impact Library for use in a Hazard Impact Model (HIM) that will operate using real-time probabilistic rainfall and surface runoff forecasts for England and Wales. The HIM provides an approach suitable for modelling flood impacts. Initial results are presented for a case study covering the 2012 floods in the North East of England. Information generated by the HIM provides additional benefits beyond current methods. Features include operator access to 1 km 15 min spatial–temporal data, analysis of individual impact criteria and modular refinement of the Impact Library to suit different situations. The HIM has been developed in partnership via the Natural Hazards Partnership.

KEYWORDS

ensemble forecasting, flooding, Hazard impact model, impact library, natural hazards Partnership, risk, surface water flooding

1 | INTRODUCTION

There is growing demand for improved risk-based surface water flooding (SWF) warning systems. This is evident in the England and Wales Flood Risk Regulations, 2009 (SI 2009/3024), which implements EU directive 2007/60/EC on the assessment and management of flood risks (Union, 2007) and calls for member states to consider both flood hazard and its impacts. In the UK, the Government's Pitt Review of the summer 2007 floods (Cabinet Office, 2008) makes recommendations for developing tools and techniques for modelling SWF, including forecasting capabilities. Expansion and intensification of urbanisation are increasing the extent and proportion of impervious surface cover in cities (Lee & Heaney, 2003; European Union, 2007; Kelly, 2014). Urbanisation has led to the growth of urban populations in both extent and density, increasing the pressure for development on floodplain areas (European Union, 2007). These factors combine to increase the exposure and risk of urban populations and properties to SWF impacts (Kazmierczak & Cavan, 2011; Schubert & Sanders, 2012; Stephens & Cloke, 2014). In the UK, recent SWF events affecting Newcastle in 2012 (Newcastle City Council, 2013) and Canvey Island in 2014 (Essex County Council, 2014) have demonstrated the impacts of SWF on communities and highlighted the difficulties associated with preparedness and response.

SWF is challenging to forecast due to the complexities of predicting convective rainfall events and the modelling of complex localised flow pathways (Moore et al., 2015). Further challenges are presented by its rapid onset and localised extent (Environment Agency, 2014a; Speight et al., 2016). Consequently, the accuracy of SWF forecasts beyond a few hours lead-time is constrained, although improvements to spatial flood hazard prediction have been made via advances in numerical weather prediction, grid-based flood modelling and probabilistic forecasting (Golding et al., 2014; Moore, Cole, Bell, & Jones, 2006). Despite these limitations, there is still value in understanding the potential impacts of flood hazards to provide more targeted information to responders (Cabinet Office, 2008; Halcrow, 2011; Ochoa-Rodriguez, Thraves, & Johnson, 2013; Stephens & Cloke, 2014). Further, Parker, Priest, and McCarthy (2011) and Dale, Davies, and Harrison (2012) state a growing requirement for rapid SWF hazard impact assessments that can be integrated into an operational environment. This includes real-time access to SWF hazard forecast data to improve response and incident management, and better inform flood defence and resilience policies (Molinari, Ballio, & Menoni, 2013).

The novel approach to SWF impact modelling discussed in this article has been developed under the Natural Hazards Partnership (Natural Hazards Partnership, 2016). The approach takes advantage of new datasets and recent developments in numerical weather prediction, hydrological modelling and probabilistic forecasting to provide more targeted flood impact and risk information. This is achieved by using high resolution precipitation forecasts from the Met Office, the grid-to-grid (G2G) hydrological model (Moore et al., 2006) developed by the UK Centre for Ecology & Hydrology (CEH) and currently in use by the Flood Forecasting Centre (2017) for assessing fluvial flood risk across England and Wales (Cole, Moore, Wells, & Mattingley, 2016; Moore et al., 2015; Price et al., 2012), and by creating a multi-dimensional off-line Impact Library developed by the Health and Safety Executive. This article expands on work by Aldridge, Gunawan, Moore, Cole, and Price (2016) in detailing Impact Library development through combining the novel assimilation of multiple SWF scenarios with a range of categorised impact data exploiting unique datasets of fine spatial detail. These improvements allow a disaggregated and focused assessment of the risks to different receptors at county/unitary authority and local scales. After outlining the proof-of-concept Impact Library, results of the SWF Hazard Impact Model (HIM) are analysed for a 2012 SWF event in North East England.

1.1 | Communicating SWF in England and Wales

The Flood Forecasting Centre (FFC) issues a daily Flood Guidance Statement (FGS) to provide information for emergency (Category 1 and 2) responders in England and Wales to assist with emergency planning and resourcing decisions (Met Office, 2015). The FGS is a daily risk assessment of flooding across England and Wales, updated more frequently as the situation demands. It provides an assessment of all natural sources of flood risk out to 5 days, identifying developing situations and considering potential threats to people, property and infrastructure. To ensure consistency of communication, the FFC use two key resources when preparing FGS advice: the Flood Risk Matrix and the Flood Impacts Table. The Flood Risk Matrix (Figure 1) provides a method for evaluating flood risk, based on an assessment of event likelihood and the potential impact severity. The Flood Impacts Table (Table 1) is used as an aid to assess the impact severity of the Flood Risk Matrix, and lists examples of flood impacts across four severities (*Minimal*, *Minor*, *Significant* and *Severe*). Likelihood is measured using probabilistic rainfall ensemble scenarios and expert hydrometeorologist judgement.

In a survey of wider UK flood risk stakeholders, Ochoa-Rodriguez et al. (2013) found that benefits could be gained from a more targeted approach to SWF warning. These

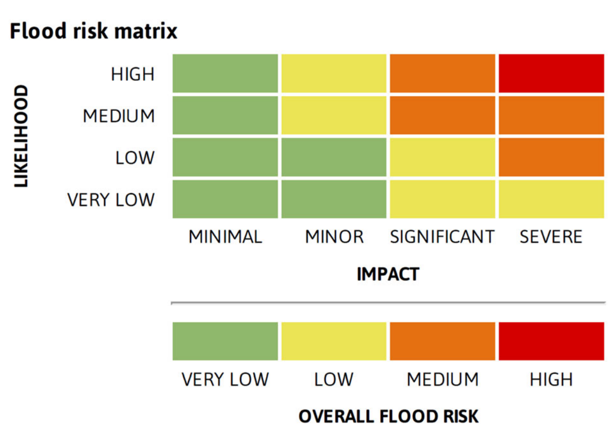

FIGURE 1 Flood risk matrix used by the Flood Forecasting Centre (2017)

TABLE 1 Flood impacts table used by the Flood Forecasting Centre (2017)

Flood Impacts table				
	Minimal impacts	Minor impacts	Significant impacts	Severe impacts
Risk to life	Not expected	Individual risk for the more vulnerable or for those making decisions in unfamiliar situations (e.g., when crossing fords or rescuing pets)	Danger to life from fast flowing/deep water/wave overtopping/wave inundation and physical hazards (e.g., getting stuck in water)	Danger to life from fast flowing/deep water/wave overtopping/wave inundation and physical, chemical or utility hazards (e.g., electrocution)
Communities	Isolated and localised flooding of low-lying land and roads	Localised flooding of land and roads	Some communities temporarily inaccessible due to flooded access routes	Communities cut off
	Isolated instances of spray/wave overtopping on coastal promenades	Localised flooding (inc. waves) affecting individual properties	Flooding affecting properties and parts of individual or multiple communities	Widespread flooding affecting large numbers of properties and whole communities
	Not expected	Local damage due to age and/or condition of structure	Damage to buildings/structures	Extensive damage to and/or collapse of buildings/structures
Transport	Little disruption to travel although wet roads and fords could lead to difficult driving conditions	Local and short term disruption to travel	Widespread or long duration disruption to travel	Widespread and long duration disruption to travel. Motorists/passengers becoming stranded
			Damage to transport network (some route closures)	Widespread damage to transport network and widespread route closures
Utilities	Not expected	Localised and short term disruption to utilities and services	Disruption to utilities and services	Widespread/prolonged disruption through loss of utilities and services

Note: This version of the table replaced the one that was current during the research described in this article, however, the entries are largely the same

included greater emphasis on potential impacts and subsequent risk levels. Parker et al. (2011) state that this improved information would assist responders in planning. For the 2014 Commonwealth Games in Glasgow, the Scottish Environment Protection Agency (SEPA) commissioned a trial that aimed to address some of these issues in an operational capacity (Moore et al., 2015; Speight et al., 2016). The trial demonstrated the first operational SWF forecasting system based on impact modelling capable of giving lead-times out to 1 day whilst acknowledging limitations on the uncertainty of SWF prediction. The approach presented information on the potential flood impacts alongside the potential flood hazard using a threshold-based approach for a series of impact categories, for a 10 by 10 km area covering much of Glasgow.

1.2 | The impact library approach

For a flood risk assessment that provides the most value to the FFC and their stakeholders, the SWF HIM needs to make the most of the available data, science and technology whilst also giving FFC hydrometeorologists sufficient time to interpret outputs and produce guidance. The challenge of reducing processing times requires a trade-off between the format and complexity of input data and the number of calculations required by the model. The approach selected for the SWF HIM was to create a pre-calculated Impact Library to reduce the processing required during model operation.

The Impact Library is constructed as a set of pre-calculated impact information for different hazard scenarios. The rationale for pre-calculating the impacts is threefold: it offers rapid computation by doing the bulk of the geographical processing in advance, allows the use of detailed geographic information from large datasets in a real-time context, and it provides a consistent and traceable baseline to aid assurance in the results. Figure 2 demonstrates how the Impact Library approach can be used to estimate the impacts of a hazard event using a gridded Impact Library with three Hazard Levels. A map of hazard information classified into Hazard Levels is split to produce binary indicator maps defining the spatial extents for each Hazard Level. The Hazard Level maps are used to select impact information from the Impact Library matched by cell location and Hazard Level. The different elements of impact information are then combined into a final map of impacts.

Use of the Impact Library with multiple Hazard Maps produces a series of Impact Maps which if combined with likelihood information may be combined to create Risk Maps. The Hazard Maps could represent different hazard scenarios, based on a single hazard type via probabilistic forecasting (as in the SWF HIM described below), or a variety of hazard types for wider multi-hazard assessment. The use of an ordinal Hazard Level (as in Figure 2) is not compulsory; the Hazard Map may also represent different hazard scenarios, hazard types, or other categorical parameters.

1.3 | Impact criteria and vulnerability

As advisors to emergency responders, the FFC are interested in the category and severity of impacts (Table 1). The impacts listed provide useful scope for an impact model and can be grouped into a set of criteria. Impact categories suggested by the EA for the assessment of local flood risk (Environment Agency, 2014a) provide a logical approach to selecting indicators of relevance to the FFC. These include counts of population impacted to measure human health (Jonkman, Vrijling, & Vrouwenvelder, 2008; Vinet, Lumbroso, Defossez, & Boissier, 2012), counts of properties and areas of land to measure economic damages (Meyer et al., 2013; Penning-Rowsell et al., 2013), and counts of infrastructure points and road lengths to measure service disruption (Hall, Henriques, Hickford, & Nicholls, 2012; Kazmierczak & Kenny, 2011).

Vulnerability is a fundamental component of risk, alongside hazard and exposure (The United Nations Office for Disaster Risk Reduction, 2017). It is defined as the characteristics and circumstances of a community, system or asset that make it susceptible to the damaging effects of a hazard. Vulnerability measures are a critical factor in calculating impact severity magnitude (Adger, 2006; Birkmann, 2006). Relevant sources of data must reflect the multi-dimensional nature of vulnerability and include demographic census data, information on flood warning effectiveness and building materials (Ciurean, Schroter, & Glade, 2013). For the present analysis, elderly and long-term ill populations are modelled as more vulnerable than other population members based on an assumption of physical vulnerability to the flood hazard. This follows the Flood Risk to People Methodology (HR Wallingford, 2005), and Tapsell, Penning-Rowsell, Tunstall, and Wilson (2002), who use age and ill-health as two key factors of the Social Flood Vulnerability Index.

2 | IMPLEMENTATION

2.1 | Case study area and event

The case study area is located in North East England as demarcated by the box in Figure 3. It extends over a 150 by 150 km square encompassing the FGS reporting

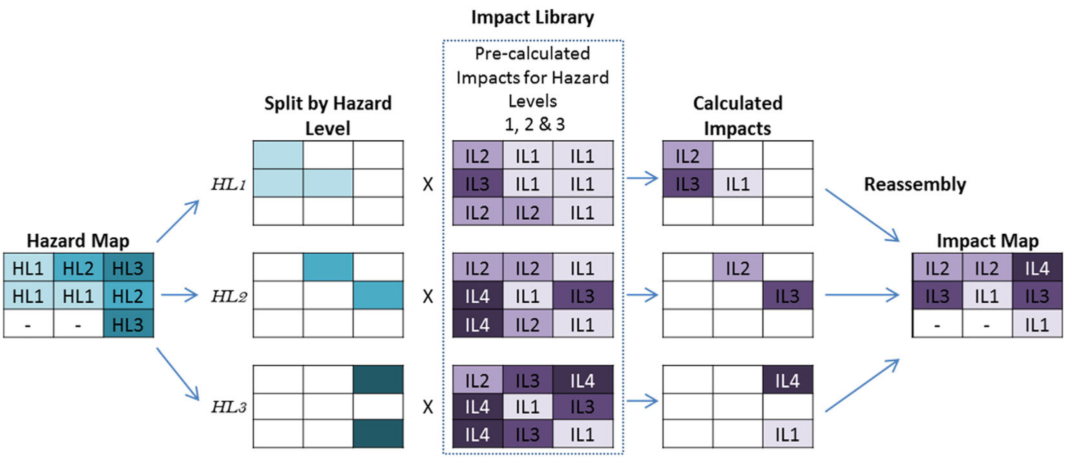

FIGURE 2 Using the Impact Library approach to calculate impacts. HL, hazard Level; IL, impact Level

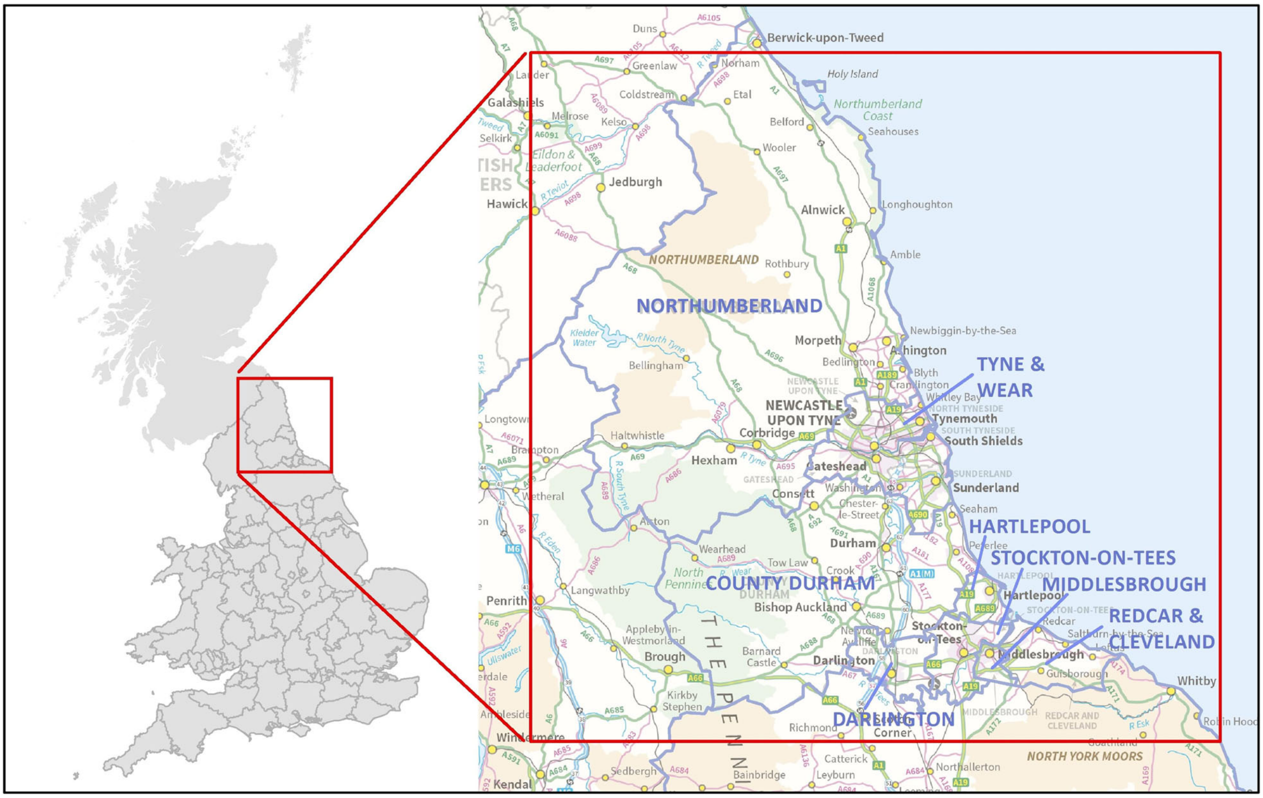

FIGURE 3 Extent of SWF HIM case study area

areas (typically counties or unitary authorities) of Tyne and Wear, Northumberland, County Durham, Darlington, Stockton-on-Tees, Hartlepool, Middlesbrough and Redcar and Cleveland.

On June 27, 2012, very warm and humid air from Europe moved northwards across the UK (Met Office, 2013). This caused significant SWF in Northern Ireland. On June 28, 2012, the emphasis shifted to central, eastern and northern England where severe thunderstorms brought locally torrential rain, large hail and further flooding from surface water and small rivers. In the morning, these storms were widespread across the south of the Midlands and the Birmingham area and moved to Cumbria, North East England and Lincolnshire later in the day. The storms cleared early in the evening of 28 June.

The main impacts of the event were seen in the north of England where hourly rainfall totals of around 30 mm were reached in the heavier storms. Isolated locations experienced 40–50 mm in 2–3 hr. The rainfall caused major disruption to infrastructure including the closure of the A1 road and many minor roads in the North East. A survey of residents by Newcastle City Council (2013) found that over 1,200 properties were impacted with over 500 being internally flooded, and there were reports of thousands of homes left without power (News Post Leader, 2012). The MetroCentre, a shopping centre in Tyne and Wear, was also reported as flooded along with many schools and shops across the North East (Cooper & Narain, 2012). There were no fatalities or serious injuries, but significant levels of stress, depression and other deterioration of health and well-being were all reported by residents (Newcastle City Council, 2013). Flooding of Newcastle Rail Station and a landslide over railway tracks outside Berwick-upon-Tweed led to suspension of train services between Durham and Edinburgh. In Newcastle, the entire light rail metro network was disrupted (Jaroszweski, Hooper, Baker, Chapman, & Quinn, 2015).

2.2 | Implementation overview

The methodology for the SWF HIM is outlined in Figure 4. This article focuses on development of the Impact Library (top right grey panel in Figure 4) and conversion of impacts into risk by reporting area (bottom grey panel in Figure 4). The top left panel in Figure 4 is the Hazard Model, which produces the Hazard Map that is used with the Impact Library to create Impact Maps (Figure 2).

The Hazard Model component of the SWF HIM is produced using the G2G distributed hydrological model with the Met Office Global and Regional Ensemble

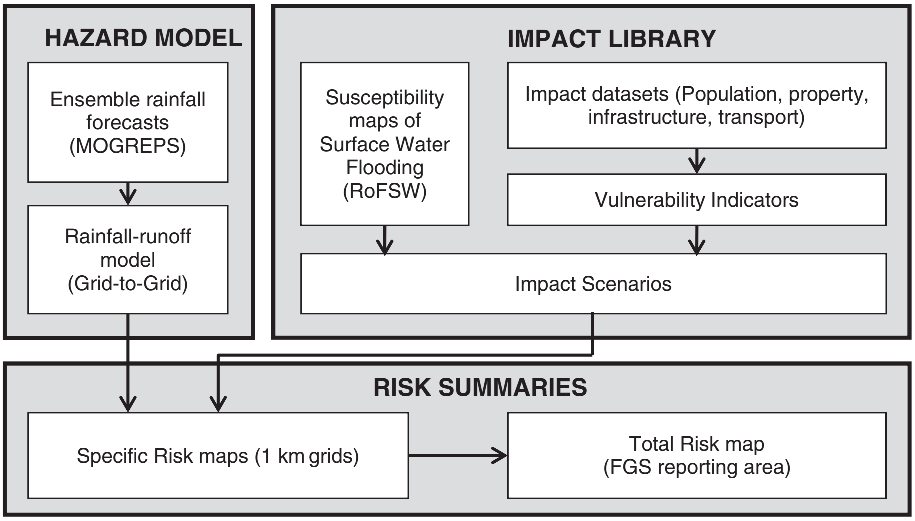

FIGURE 4 Overall methodology for the SWF HIM and its Impact Library

Prediction System (MOGREPS; Met Office, 2014) providing ensemble rainfall forecast inputs. MOGREPS produces probabilistic weather forecasts at a global and regional scale. At the UK regional scale, the forecasts have a spatial resolution of 2.2 km. In the G2G model, an estimate of surface runoff is produced for each 1 km grid-cell at 15 min intervals. Spatial datasets on landscape properties (derived from terrain, soil, geology and land-cover data) underpin the G2G model configuration and, together with continuous accounting of soil moisture, control surface runoff generation from rainfall (Cole, Moore, & Mattingley, 2015; Moore et al., 2006).

The SWF HIM Impact Library includes layers of geographical gridded impact information organised by impact criteria and a Hazard Level defined by flood hazard return period. The grid resolution is 1 km, aligning with the Hazard Model outputs.

The Risk Mapping component describes the risk outputs of the SWF HIM. The Specific Risk maps are a collection of 1 km gridded outputs reporting levels of impact severity for each ensemble member, by impact criteria. The Total Risk map summarises the Specific Risk information to report risk as a function of impact and likelihood, by reporting area.

The following spatial datasets were used to create the Impact Library for the SWF HIM case study.

2.2.1 | Risk of Flooding from Surface Water maps

The *Risk of Flooding from Surface Water* (RoFSW) mapping from the Environment Agency (2013) provide the SWF hazard susceptibility maps used to estimate the potential extent and intensity of flooding. The RoFSW details the worst case flood extents for defined events based on three rainfall probabilities (1 in 30 year, 1 in 100 year and 1 in 1000 year) and three different storm durations (1, 3 and 6 hr) at a pixel resolution of 2 m. The RoFSW data reports flood characteristics including depth (m), velocity (m/s), flow direction and a hazard rating score as a function of depth and velocity (HR Wallingford, 2005). This research used the the maximum-value RoFSW datasets; one for each return period.

2.2.2 | The National Population Database

The National Population Database (NPD) models the locations of population in the UK (Smith, Arnot, Fairburn, & Walker, 2005). It was originally developed to support the Health and Safety Executive in its regulation of major hazard installations (Smith et al., 2005; Smith & Fairburn, 2008), but has since been used in other contexts including the assessment of potential impacts from accidents at major hazard sites (Aldridge, Cruse, & Roche, 2014), and evaluation of flood risk (Cole, Moore, Aldridge, Lane, & Laeger, 2013; Pilling et al., 2014). The NPD combines population and attribute information from a range of sources including government datasets and the census, attaching them to ordnance survey (OS) location data for geographical analysis. The population layers are organised into five themes: Residential, Workplace, Sensitive (categorised into schools, hospitals, care homes, childcare and prisons), Transport (including roads and terminals) and Leisure (including visitor attractions, stadiums, and retail).

2.2.3 | The National Receptor Dataset

The National Receptor Dataset (NRD) is produced by the EA as a collection of risk receptors (Environment

Agency, 2010). The NRD is primarily intended for flood and coastal erosion risk management purposes and was developed to evaluate flood damage at regional or national scale. Version 1 of the NRD property point data provides information on every property in England and Wales that has a corresponding record in OS Address Layer 2 (which includes addressable and non-addressable locations), or has a footprint greater than 25 m^2. Version 1 of the NRD (released 2005) was used for this case study. The building information in the NRD includes classifications for the Multi-Coloured Manual (Penning-Rowsell et al., 2005, 2013) which was used to flag infrastructure and determine building use.

2.3 | Impact criteria measurements

Functions for damage, danger and denial of access were used to provide quantitative indicators of the impact for each impact criteria. Danger to life impacts were evaluated as the number of people at risk, based on a sum of NPD estimates at locations that exceeded RoFSW hazard rating thresholds. The hazard rating HR was calculated as

$$HR = d(v + 0.5) + DF \quad (1)$$

where d is depth of flooding (m), v is velocity of floodwaters (m/s) and DF is a debris factor, which ranges from 0 to 1 depending on water depth and land use. The hazard rating is grouped into four categories of severity as indicated in Table 2 (HR Wallingford, 2005).

Impacts on population were considered for day time and night time population scenarios based on NPD configurations outlined in Table 3.

Populations were deemed at risk if exposed to a flood hazard rating of 1.25 or greater (categorised as *Significant* flood hazard), with more vulnerable populations at risk if the hazard rating exceeded 0.75 (*Moderate*, dangerous for some [i.e., children]), based on the classifications detailed in Table 2. Populations more vulnerable to the flood hazard were identified as a subset of the NPD sensitive layers.

Damage to buildings was assessed using a flood depth threshold to estimate numbers of buildings at risk of flooding. NRD building locations were counted as flooded if the property point location intersected a flood depth exceeding 0.3 m, based on the typical height of a step. The metrics used for damage to buildings were counts of residential and non-residential buildings impacted.

Key sites and infrastructure impacts were estimated as counts of selected NRD locations within flooded areas. Table 3 details the selection of key sites and infrastructure classifications. Denial of access to infrastructure was determined based on a spatial intersection with flooded areas modelled to exceed a hazard rating threshold of 1.25 (*Significant*). Denial of access to key sites was based on the same function as that for assessing building damage.

TABLE 2 Hazard categories (Environment Agency and HR Wallingford, 2008)

Hazard rating	Degree of flood hazard	Description
0.575–0.75	Low	Caution *"Flood zone with shallow flowing water or deep standing water"*
0.75–1.25	Moderate	Dangerous for some (i.e., children) *"Danger: Flood zone with deep or fast flowing water"*
1.25–2.00	Significant	Dangerous for most people *"Danger: Flood zone with deep fast flowing water"*
>2.00	Extreme	Dangerous for all *"Extreme danger: Flood zone with deep fast flowing water"*

The road and rail network were the focus for the transport impact criteria based on intersections of flooded areas with the NRD transport datasets. Transport links were deemed to be disrupted by flood water if the link was intersected by a flood depth of 0.15 m or higher for a distance of 10 m. This flood depth is a conservative estimate for roads becoming impassable or closed, based on a typical ground clearance for a current small or family car (SoftNews NET, 2017). The effects of a road blockage extend beyond the flooded section, so the length of the full network link affected was used as the impact metric for the Impact Library.

The final Impact Library metrics are listed in Table 3. Processing of the data was undertaken using ArcGIS and MapInfo and the results summarised for each 1 km cell in the study area.

2.4 | Measuring impact severity

To aid rapid assessment of flood risk information produced by the SWF HIM and allow comparison of different impact criteria, impact severity metrics were standardised. The values in Table 4 present impact criteria severity thresholds for each 1 km cell. Initial thresholds were proposed based on interpretation of the Flood Impacts Table (Table 1),

TABLE 3 Impact metrics stored in the SWF Impact Library

Criteria	Data source	Impact metric (per 1 km cell)	Impact criteria detail	
Danger to life	NPD	Count of people at risk	Day time population:	Day time term-time Residential Workplaces Schools/Care Homes Hospitals/Prisons
			Night time population:	Night time term-time Residential Care Homes Hospitals/Prisons
Damage to buildings	NRD	Count of properties at risk	Residential properties Non-residential properties	
Denial of access to key sites/ infrastructure	NRD	Count of sites at risk	Key sites:	Schools/Colleges/Universities Surgeries/Health Centres Residential home Fire/Ambulance/ Police Stations Hospitals
			Infrastructure:	Electrical installations Gas regulating facilities Water treatment works
Denial of access to transport networks	NRD	Length of network at risk (m)	Trunk roads Non-trunk A/B road Railway	

TABLE 4 Impact thresholds proposed for the SWF HIM

	Impact severity level			
Impact criteria	Minimal (1)	Minor (2)	Significant (3)	Severe (4)
Danger to life (count)	0	40	200	300
Damage to buildings				
• Residential (count)	0	5	30	100
• Non-residential (count)	0	1	10	30
Disruption of key sites (count)	-	0	1	2
Disruption of infrastructure (count)	0	1	2	4
Disruption of transport				
• Trunk roads and motorways (metres)	0	150	500	1800
• Other major roads (metres)	0	500	1800	-
• Railways (metres)	0	300	950	-

aligned to those adopted for the creation of the EA "blue squares" map employed in the Surface Water Flood Decision Support Tool, currently used by FFC (Halcrow, 2011). Threshold values were refined based on expert advice from stakeholders at the FFC. It is acknowledged that SWF impacts on railways can be considered *Severe*, however the maximum was set to *Significant* in this SWF HIM as the rail methodology is limited for modelling the widespread impacts on the rail network. Further validation and sensitivity testing is required before these values can be used in an operational setting, but they are sufficient for this case study. An impact severity level (*Minimal*, *Minor*, *Significant* and *Severe*) and corresponding score (*1*, *2*, *3* and *4*) was attributed to each cell based on exceedance of the threshold values in Table 4. A value of *0* was attributed to cells where no threshold was exceeded.

2.5 | Aggregating impact criteria results

A disjunctive Multi-Criteria Analysis approach (Meyer, Haase, & Scheuer, 2007) was adopted for combining impact severity levels from the different criteria. This has similarities with the single threshold hotspot method proposed for local flood risk assessment by the Environment Agency (2014a). Each 1 km cell was allocated the highest risk score of all contributing impact criteria. The disjunctive approach does not account for compounds of impact criteria, for example where a union of multiple *minor* severity impacts might combine to a *significant* severity. The approach was adopted as a pragmatic compromise, with stakeholder agreement; the disjunctive approach providing an immediate focus in a time-critical forecasting situation.

2.6 | Analysis of SWF HIM against a forecast SWF event

For the case study, G2G surface runoff information for 1 km cells over a 24-hr forecast window was produced using a 12-member rainfall forecast ensemble updated four times per day. The runoff information included summaries for 4 forecast lead-time windows (0–6, 6–12, 12–24 and 0–24 hr), for the following 12 forecast origin times:

- June 26, 2012 (00:15, 07:15, 12:15, 19:15)
- June 27, 2012 (00:15, 07:15, 12:15, 19:15)
- June 28, 2012 (00:15, 07:15, 12:15, 19:15)

Analysis of the Impact Library against these data follows Figure 2. Runoff information required by the Impact Library was obtained by calculating the maximum rainfall accumulation for a given duration over the forecast lead-time window and associating this with a return period exceedance by reference to the RoFSW. The return period information fulfils the role of the Hazard Level and was used to provide impact maps for each criterion. This process was replicated for each ensemble member to produce 12 impact maps for each forecast time.

2.7 | Summary of results and measure of risk

The final 1 km impact severity maps are not straightforward to interpret and appear "noisy" due to background geographical factors that combine with flood impact estimates. Further, presentation of the outputs at a 1 km resolution may transfer a perception of false accuracy, beyond the spatial accuracy of the precipitation forecast. Consequently, the 1 km grid-cell impact results were summarised by the reporting area used within the FGS, providing more meaningful and accessible information for emergency response. The aggregation approach taken for this process used a threshold, n, defined as the number of cells within a reporting area that are required to exceed a given impact severity: *minor*, *significant* or *severe*. This is calculated as.

$$n = A\left(\frac{p}{100}\right) \tag{2}$$

where A (km^2) is those parts of the reporting area, that combined, have the potential to be subject to impacts of *minor* severity or greater. The value of p determines the minimum percentage of cells within a reporting area that need to be exceeded for a given impact severity. For the results presented here, p was assigned a value of 1, which reflects the 99th centile of the reporting area. The minimum value of n was set at 1.

Each reporting area is attributed the most severe impact level where the cell count exceeds n. A *minimal* severity is assigned if n is not exceeded. The derivation of A excludes areas where there are no pre-calculated impacts in the Impact Library within any of the impact criteria. This provides consistency of the summary across reporting areas of different sizes and impact potential.

The SWF risk for each reporting area is derived by counting the number of ensemble members that exceed each impact severity. The counts are expressed as a percentage of ensemble members to provide the measure of likelihood used to determine the position on the y-axis of the Flood Risk Matrix (Figure 1), as used by the FFC: Very Low ≤20%, Low = 20–40%, Medium = 40–60%, High ≥60%. The *x*-axis is determined by the given hazard severity. This reporting area risk forecast can then inform the assessment undertaken by the FFC in the surface water flood risk guidance provided in the FGS. For this article, the highest level of risk attained is used to represent the overall flood risk assigned (Figure 1).

3 | RESULTS

3.1 | Reporting area summaries

Figure 5 illustrates county/unitary authority risk summary results for a 0 to 24 hr forecast window, for 12 time-steps over a 3-day period. Colours represent risk, based on the Flood Risk Matrix (Figure 1). After a lead-in period of mostly *very low* risk (green), the impact model outputs indicate that the key SWF risks appear in the forecasts for 27 June (19:15) and 28 June (00:15 and 07:15). On 27 June (19:15), a *medium* risk (amber) is allocated to Darlington and Durham based on *medium* likelihood of *significant* impacts. The 28 June (00:15) forecast presents m*edium* risks (amber) for Northumberland (*high* likelihood of a

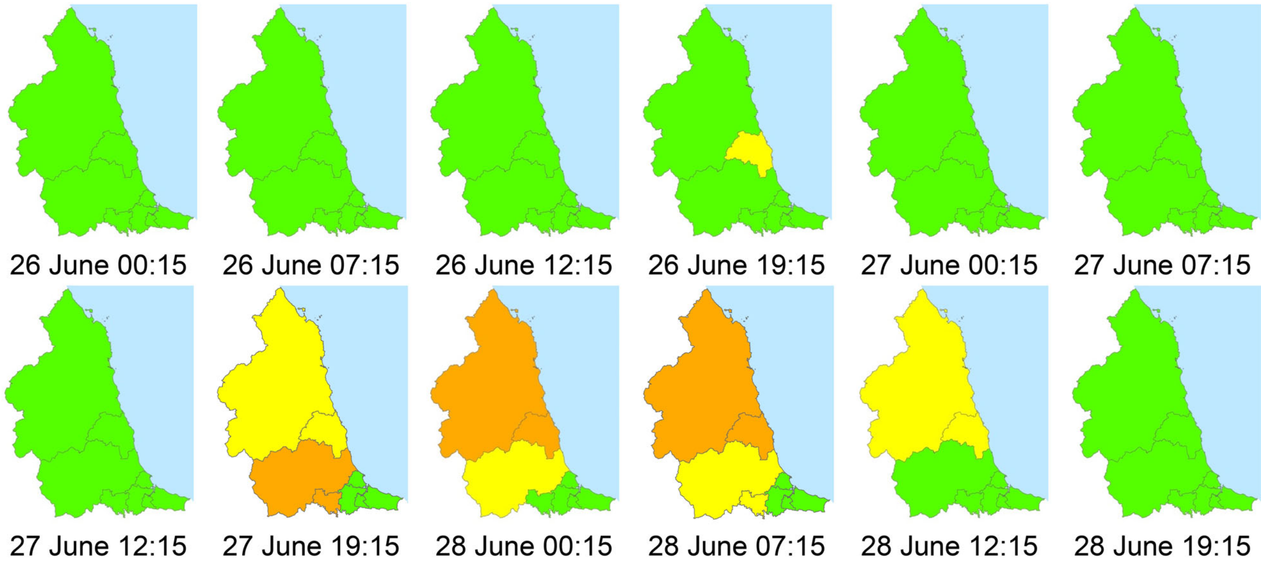

FIGURE 5 Area-level summaries for the case study across the 3 days of forecasted rainfall. Colours indicate levels of risk. Green, very low; yellow, low; amber, medium. No high (red) level risks were forecast

significant impact) and Tyne and Wear (*medium* likelihood of a *significant* impact). The 28 June (07:15) forecast assigns *medium* risk (amber) to Northumberland (*medium* likelihood of a *significant* impact) and Tyne and Wear (*high* likelihood of a *significant* impact).

Table 5 presents histogram information for the 0–24 hr forecast lead-time period, for the second and third days of the forecasts analysed limited to the four counties in the case study area with risk levels of *low* (yellow) and *medium* (amber). The values in the table are counts of ensemble members (maximum 12) that exceed each impact severity, for each forecast origin time. The colours represent the highest level of overall flood risk, based on the Flood Risk Matrix (Figure 1).

3.2 | 1 km summaries

The SWF HIM 1 km cell summaries are calculated as the maximum impact severity by criteria across the ensemble rainfall forecast. Figures 6–9 present the 1 km cell summaries for the four most active forecasts (identified by their origin times) for the 0 to 24 hr forecast lead-time window, centred on the County of Tyne and Wear. The maximum of all criteria is also included. Table 6 presents cell counts for Tyne and Wear for the four forecasts, split by impact criteria and impact severity level.

The 1 km summaries show the widest geographical spread and the highest levels of intensity on June 28, at 00:15 and 07:15 (Figures 7 and 8). The location of the most severe impacts is consistent for both forecasts. Property is shown to be the most active impact criteria for these forecasts for all levels of impact severity with impacted cells modelled across the area, including 4 red (*severe* impact), and 28 amber (*significant* impact). For the most heavily affected forecast (June 28, 00:15, Figure 7), there are 170 property-impacted cells compared to 35 for transport, 11 for population and 1 for key sites and infrastructure (Table 6). The red (*severe impact*) property cells in the figures represent large numbers of buildings at risk and cover large industrial estates and dense town centre areas. The population criteria also contribute a red cell to the overall maximum summary for the first three forecasts. This is identified as a school population within an area of flood hazard. Transport impacts are modelled as *minor* or *significant*, with trunk routes affected.

4 | DISCUSSION

4.1 | The SWF HIM for operational flood forecasting

The SWF HIM is capable of providing rapid, area-based risk summaries for SWF across England and Wales. This represents a useful additional tool for the FFC to support decision-making on the overall flood risk for the FGS. Further, new insights into flood risk composition can be made through deeper analysis of the four impact criteria, the underlying 1 km cell summaries, and the lead-times offered. These allow the assessment of localised impact severities and evaluation of the changing flood scenario in much greater detail.

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TABLE 5 Histogram information detailing the count of ensembles that exceed each level of impact severity over time, for four counties

Forecast Origin (June 2012)	Darlington				Durham				Northumberland				Tyne and Wear			
	Minimal	Minor	Significant	Severe	Minimal	Minor	Significant	Severe	Minimal	Minor	Significant	Severe	Minimal	Minor	Significant	Severe
27th 00:15	12	0	0	0	12	0	0	0	12	0	0	0	12	0	0	0
27th 07:15	12	0	0	0	12	0	0	0	12	0	0	0	12	0	0	0
27th 12:15	12	0	0	0	12	0	0	0	12	0	0	0	12	0	0	0
27th 19:15	12	6	5	0	12	8	5	0	12	10	3	0	12	5	3	0
28th 00:15	12	0	0	0	12	3	3	0	12	12	10	1	12	7	6	1
28th 07:15	12	4	2	0	12	8	4	0	12	10	7	0	12	8	8	1
28th 12:15	12	0	0	0	12	0	0	0	12	6	1	0	12	2	1	0
28th 19:15	12	0	0	0	12	0	0	0	12	0	0	0	12	0	0	0

Note: Colours indicate the risk rating based on the flood risk matrix.

The Impact Library approach aims to extract maximum value from the high-resolution RoFSW dataset by coupling it with rainfall and surface runoff forecasting outputs produced at a coarser scale. The use of the RoFSW dataset adds a level of detailed flood risk information, previously unavailable at this scale (Speight et al., 2016). Although computational storage and processing costs associated with using this dataset are high, the demanding processing of local-level impacts is completed offline and in advance. This creates recognisable gains in resource requirements and timeliness of forecast outputs.

This article proposes technical and scientific advances in SWF risk modelling, but there are still organisational and administrative issues that need to be addressed to realise the full potential of these solutions. For example, Parker et al. (2011) stated that there is demand for improved SWF warning systems from professional emergency responders but there was also concern regarding uncertainties in the process. In particular, they recognise an issue with communicating flood warnings to raise public awareness. This research has contributed towards this through the direct adoption of the Flood Risk Matrix (Figure 1) in the model's treatment of risk and uncertainty. Embedding this in the process provides an important link from the model to the advice provided by the FFC.

4.2 | Impact library format

The Impact Library presents a platform of impact layers that includes raw, descriptive impact metrics such as counts of potentially flooded assets alongside standardised ratings for impact severity and risk categories. These data provides the SWF HIM with increased capacity to represent patterns that emerge across receptors and across impact severity levels. This is achieved through access to the separate impact criteria at multiple spatial and temporal resolutions. For example, the analysis of 1 km cell impacts (Section 3.2) could allow a more targeted focus on cell-level impacts complementing the regional impact analysis.

The flexibility of the Impact Library's modular structure, coupled with the transparency of the disjunctive MCA approach to standardisation and the relatively low operational processing costs, eases the process of Impact Library refinement. This includes updates of individual layers and impact thresholds, and application of bespoke forecasting scenarios. Sensitivity analysis would help to improve model calibration. In particular, there is value in analysing the occurrence and sensitivity of the most severely impacted cells to determine how influential they are in the overall risk analysis.

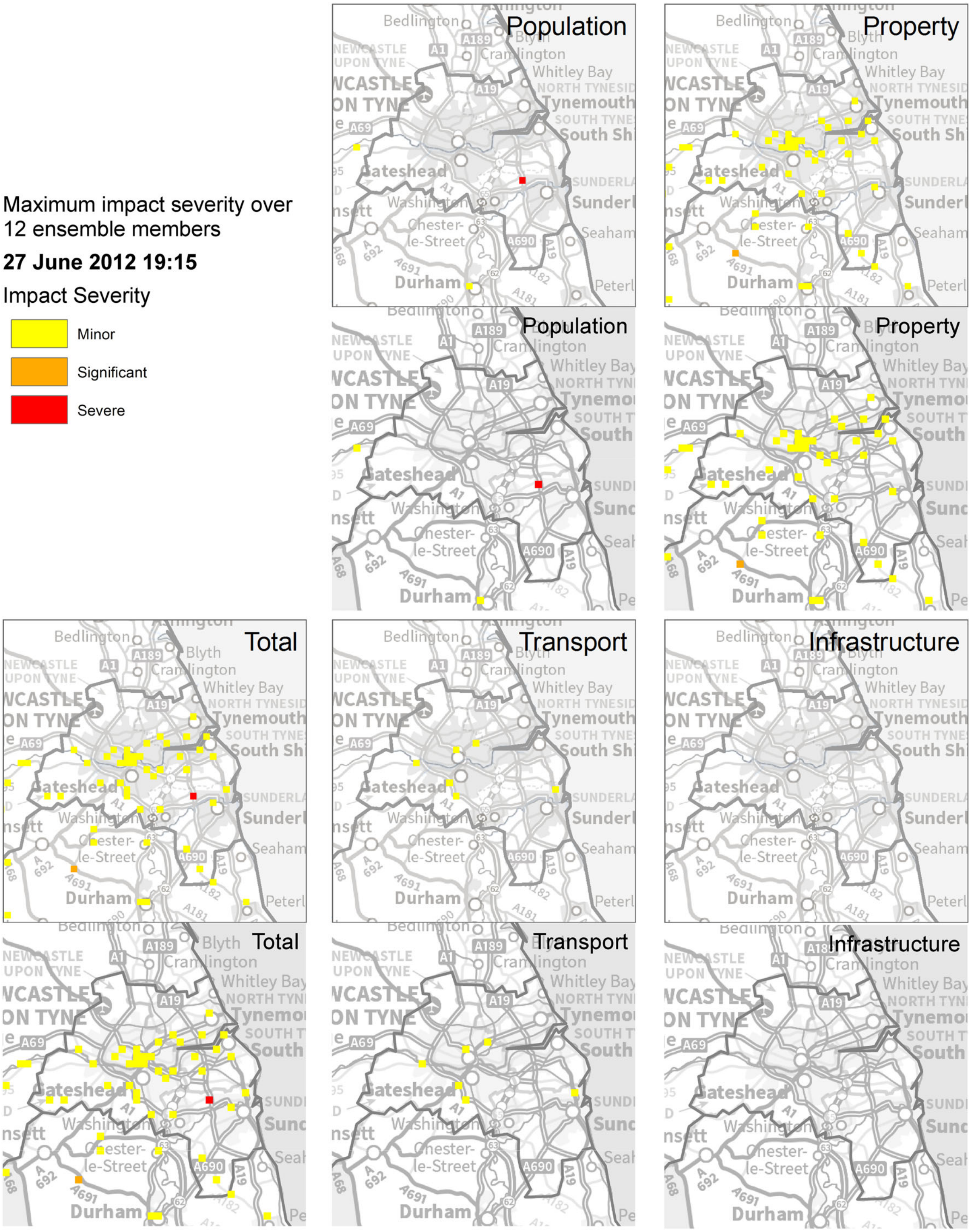

FIGURE 6 Individual impact criteria and total summaries (maximum scores) at 1 km cell level centred on Tyne and Wear for the June 27, 19:15 forecast (0–24 hr lead-times)

4.3 | Measuring vulnerability

Vulnerability mapping is a key factor in this study as it defines how an exposed receptor responds to the hazard. For danger to life assessment, the approach considers the specific vulnerability of different populations, which allows more vulnerable populations such as care homes and hospitals to be modelled appropriately. However, the literature widely cites the alternative approach of vulnerability index development based on multi-criteria data. This may be useful for characterising social and psychological impacts and also as a method of presenting

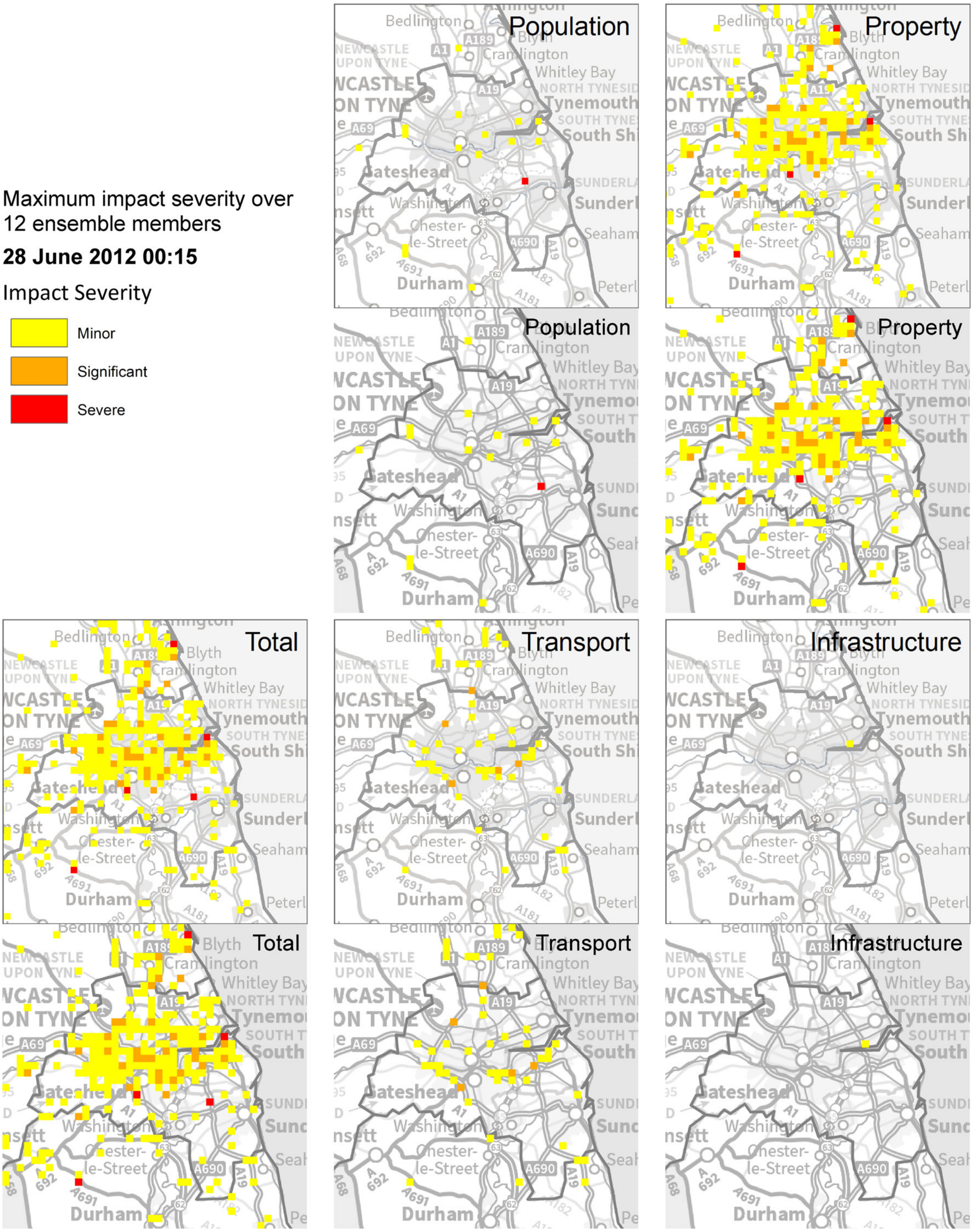

FIGURE 7 Individual impact criteria and total summaries (maximum scores) at 1 km cell level centred on Tyne and Wear for the June 28, 00:15 forecast (0–24 hr lead-times)

vulnerability in relative terms rather than as absolute values. Examples include research by Cutter, Boruff, and Shirley (2003) on the Social Vulnerability Index, or Tapsell et al. (2002) on the UK-based Social Flood Vulnerability Index. To further enrich the Impact Library, it may be relevant to include cultural and psychological impacts such as loss of unique cultural heritage (Tarraguel, Krol, & van Westen, 2012), or life satisfaction measures related to housing market decreases in impacted areas (Luechinger & Raschky, 2009). However, these metrics are challenging to quantify and interpret, and consequently may have limited utility in a forecasting situation.

Alternatively, monetary and economic measures could be used in preference to physical human impacts

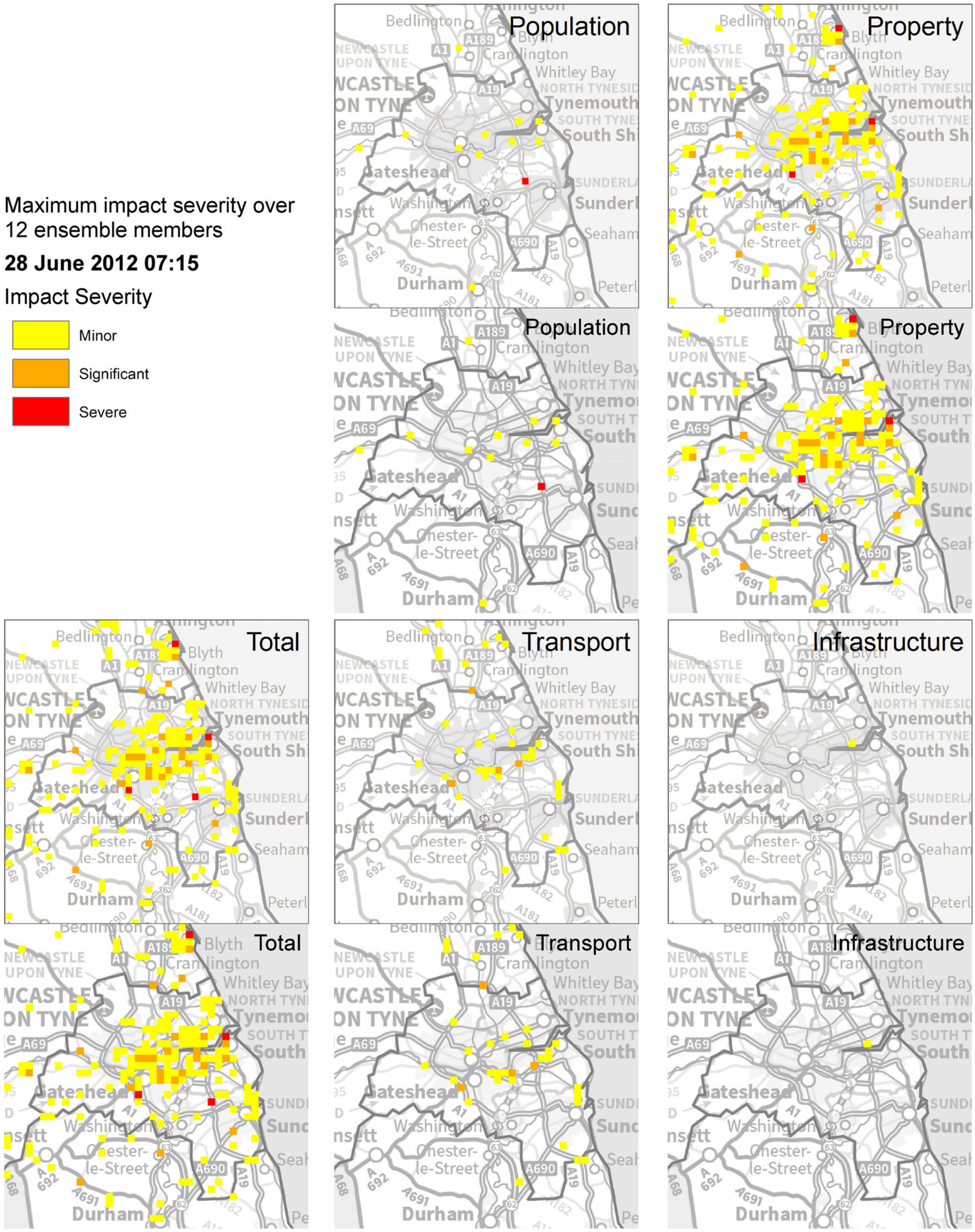

FIGURE 8 Individual impact criteria and total summaries (maximum scores) at 1 km cell level centred on Tyne and Wear for the June 28, 07:15 forecast (0–24 hr lead-times)

(Meyer et al., 2013; Penning-Rowsell et al., 2013). These could serve to standardise severities across impact criteria, but would require a robust justification on economic measurement methods. They may also introduce bias towards more wealthy areas, where a smaller number of properties would raise higher impact severities (Jonkman et al., 2008). This could contribute to increasing flood disadvantage by deprioritising the impacts on less wealthy, vulnerable neighbourhoods (Kazmierczak, Cavan, Connelly, & Lindley, 2015).

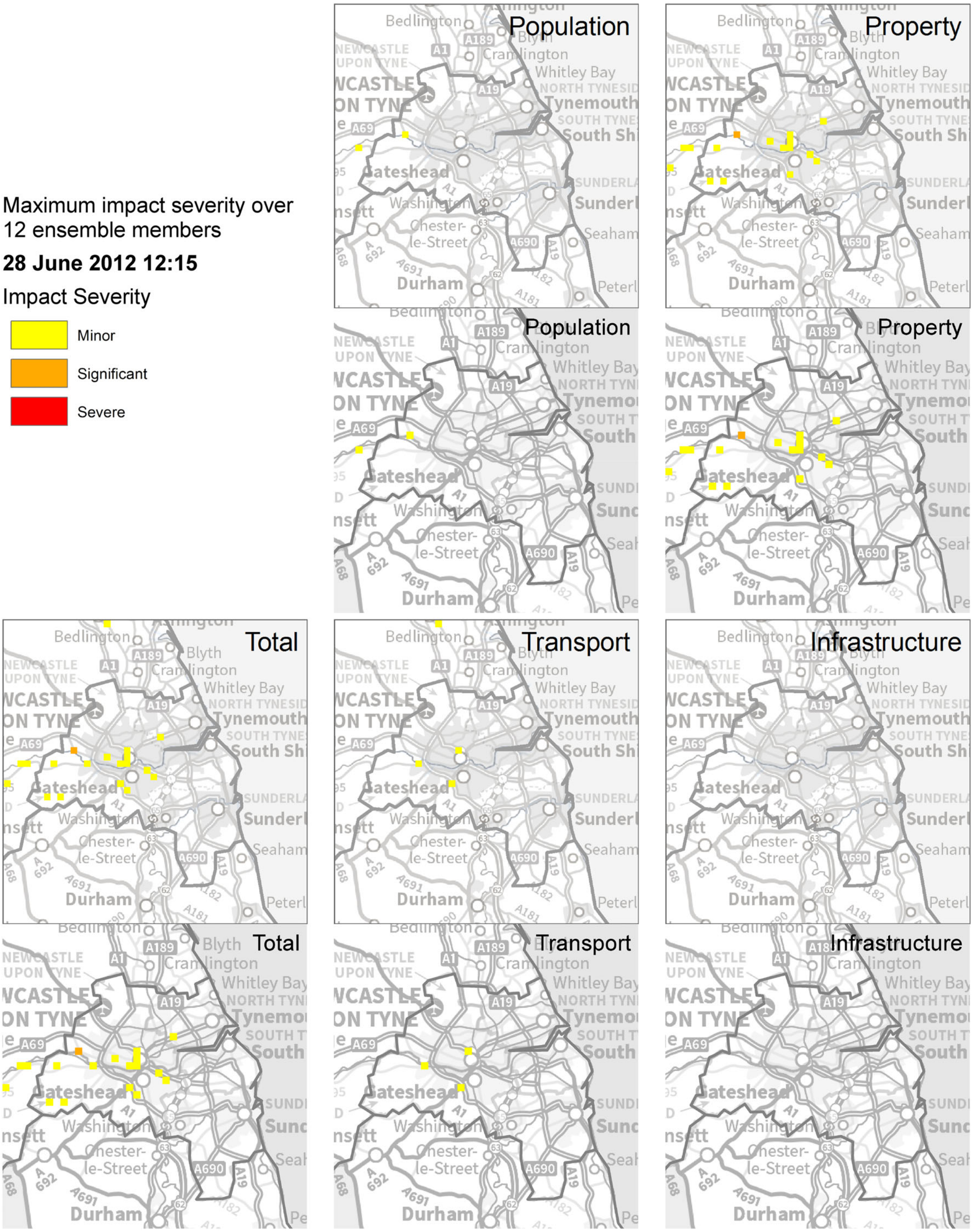

FIGURE 9 Individual impact criteria and total summaries (maximum scores) at 1 km cell level centred on Tyne and Wear for the June 28, 12:15 forecast (0–24 hr lead-times)

4.4 | Risk assignment

Use of the Flood Risk Matrix (Figure 1) to assign risk levels based on ensemble forecasts poses challenges and opportunities for interpretation. Figure 10 demonstrates that the same risk level can be derived from different combinations of likelihood and impact. For example, A and B are both *Low Risk* scenarios, but A represents a *high* likelihood of a *minor* impact forecast, while B represents a *very low* likelihood of a *severe* impact forecast. The implication for forecasters and responders is significant as the response required may be very different. To add

TABLE 6 Count of cells for each impact severity level, by impact criteria, for Tyne and Wear

Forecast step	Total			Population			Property			Transport			Key sites and infrastructure		
Impact severity	Minor	Significant	Severe	Minor	Significant	Severe	Minor	Significant	Severe	Minor	Significant	Severe	Minor	Significant	Severe
June 27, 19:15	36	0	1	0	0	1	31	0	0	6	0	0	0	0	0
June 28, 00:15	155	24	0	10	0	1	146	22	2	30	5	0	1	0	0
June 28, 07:15	108	18	3	8	0	1	101	15	2	22	3	0	1	0	0
June 28, 12:15	14	1	0	4	0	0	14	1	0	3	0	0	3	0	0

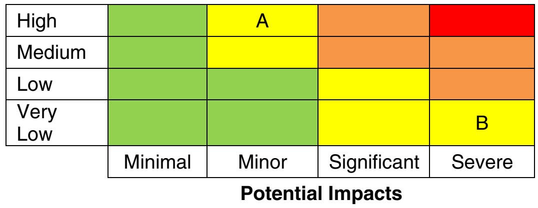

FIGURE 10 Flood risk matrix: A and B return the same risk level based on contrasting forecast information

further complication, the same risk composition could be the result of very different spatial and categorical patterns of impact. Consequently, the 1 km data provided by the SWF HIM is valuable for deeper analysis. These issues are recognised by the FFC and are accounted for in the guidance provided, but the forecast information provided by the SWFHIM will significantly enhance this assessment.

4.5 | Further impact library applications and development

The Impact Library approach has restrictions imposed by the standardised 1 km grid-cell structure. Impacts that cross cell boundaries are not straightforward to assess or visualise in the Impact Library. However, the Impact Library concept does not need to be constrained in this way. Where operational time requirements become less restrictive, for example during post-event analysis, more detailed impact evaluations and more sophisticated spatial analysis techniques could be applied to areas of interest, while secondary impacts or network and infrastructure disruption could be assessed via secondary impact models as a post-processing operation.

Future analysis will assess the viability of more sophisticated flooded property modelling such as those adopted by the EA for SWF property counts, based on proportion of flooded property perimeter rather than flooding at a point (Environment Agency, 2014b; Horritt Consulting, 2013). Modelling of transport and infrastructure impacts could benefit from further refinement as the impact of disruption is not easily quantified from a risk perspective. Finally, alternative approaches for the population criteria could be considered to better account for temporal variation and transience, especially for population groups that may be located outside of buildings. These include commuters, shoppers and tourists. Development of the NPD in combination with gravity model based approaches such as the University of Southampton's 24/7 model (Martin, Cockings, & Leung, 2015; Smith, Martin, & Cockings, 2014) could provide more realistic population estimates.

5 | CONCLUSIONS

This article demonstrates a novel Impact Library approach for modelling SWF impacts in an operational context. The HIM demonstrates improvements in the spatial and temporal resolution of SWF warning systems, responds to policy drivers from the UK Government (Cabinet Office, 2008; Flood Risk Regulations, 2009), and calls from the scientific community (Ochoa-Rodriguez et al., 2013; Parker et al., 2011). Linking rainfall forecasts to static information on flood risk via G2G means that a large proportion of processing was undertaken in advance, with potential benefits in terms of computational resources and timely delivery in a forecasting situation. The pre-processing approach is implemented here through the creation of an Impact Library, which stores potential impact information ready for use in the full SWF HIM. Further, the 1 km resolution of the impact criteria maps can provide new insights for forecasters including the capability to assess localised impact severities and evaluate the coverage of flooding in much greater detail.

Future phases of work focus on further validation of HIM outputs against independent sources, conducting sensitivity analyses to identify key variables and limitations, and refinement of impact measures. Success of the tool and its adoption within a forecasting environment is dependent on this planned development. Effective communication of SWF risk information is also vital to its success. The proof-of-concept has drawn attention to the amount of data that it is possible to produce with such tools, which encapsulate multiples of impact criteria, forecast lead-times and ensemble forecast members. Managing this information effectively is important if it is to be exploited to its full potential.

This article has demonstrated the Impact Library within an operational forecasting setting. If decoupled from the forecasting component, the Impact Library concept and data layers could be applied to other contexts. Using rainfall information, this might include scenario planning and risk assessment activity for SWF. Additionally, the capability for easily creating multiple impact scenarios that include a high level of detail means that there is potential for probabilistic assessments built on detailed high-resolution flood data. The Impact Library concept can be broadened further for other hazards, both natural and man-made. This is an area of ongoing development within the Natural Hazards Partnership.

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DATA AVAILABILITY STATEMENT

Data sharing is not applicable to this article as no new data were created or analysed in this study.

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