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Surface water flood forecasting for urban communities

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Executive Summary

Key findings and recommendations

- This research has addressed the challenge of surface water flood forecasting by producing the UK's first operational surface water flood risk forecast with a 24-hour lead time. This was successfully used in Glasgow at the Commonwealth Games in 2014.
- The methodology of the Glasgow Pilot has been developed to use nationally available datasets and a transferrable approach which will help urban areas in Scotland improve their resilience to and preparedness for future flooding.
- It also delivered a novel method for forecasting the impacts of flooding in real-time and increased knowledge on communicating uncertainties in flood risk.
- A real-time forecasting system for surface water flooding from intense rainfall needs to use models that represent surface runoff production, surface water inundation and movement, and how water travels via surface and sub-surface pathways, including urban sewerage and drainage networks. Ensemble rainfall prediction models are key to quantifying uncertainty in forecasting the rainfall that causes surface water flooding.
- Detailed surface water flood inundation models exist and are widely used in design and research activities, but none were found to be ready for real-time use. The Grid-to-Grid (G2G) distributed hydrological model was chosen for used in the Glasgow Pilot as it can provide ensemble forecasts of surface water flooding, and takes account of the intensity and pattern of rainfall, land cover and slope, and antecedent conditions.
- The research developed a novel methodology for impact assessment that links surface runoff to the severity of flooding impacts on people, property and transport. Use is made of a library of information based on SEPA's Regional Pluvial (rainfall-related) Flood Hazard maps.
- For the Glasgow Pilot, G2G was operated over a 10km by 10km area encompassing Glasgow's East End and the main areas of activity for the 2014 Commonwealth Games. The research team developed an operational application, called FEWS Glasgow, to support running the model in real-time and reporting on the likely impacts of surface water flooding. A new Daily Glasgow Daily Surface Water Flood Forecast was designed and produced based on operational requirements and emergency responder feedback.

Rationale for the research

In recent years there have been regular occurrences of pluvial flooding in Scotland, which is caused by intense rainfall over urban areas in amounts that exceed the capacity of drainage systems. Real-time surface water flood forecasting in urban areas is particularly challenging because of its origins in convective rainfall. Such rainfall results from instability of the atmosphere, and is often highly localised and notoriously difficult to forecast. As runoff and drainage processes in urban areas are highly complex, forecasting surface water flooding demands sophisticated modelling approaches to capture the full picture.

When this research began, the existing surface water forecasting capabilities of the Scottish Environment Protection Agency (SEPA) included alerts for broad areas. Alerts are based on both indicative rainfall thresholds and local hydrometeorological knowledge. No formal surface water forecasting models were in use.

Research aims and objectives

SEPA has a commitment to increase understanding of surface water flooding mechanisms and to develop appropriate forecasting and warning capabilities. The project was driven by requirements under SEPA's Flood Warning Strategy to create surface water forecasting capabilities that are at the forefront of science developments in Scotland; and specifically to scope the development of hydrological modelling capabilities in urban areas to forecast (in real-time) surface water flooding.

The overall aim of the project was to review the current state-of-the-art in surface water flood forecasting for urban communities and to develop a potential methodology for real-time surface water flood forecasting in Scotland. This methodology was to be tested through a pilot application for a known flooding area in Glasgow's East End, operating in real-time to provide strategic flood guidance during the 2014 Commonwealth Games. The project would assess how the method could be integrated into SEPA's existing flood forecasting platform, FEWS Scotland, and assess how it could be rolled-out to other areas, including identifying any barriers to roll-out.

Where Next?

The methodology of the Glasgow Pilot has been developed to use nationally available datasets and a transferrable approach. Formal assessment of the probabilistic tools will take longer, but identified benefits of using the new approach include (i) indicating flood risk is unlikely for Glasgow when regional guidance does, and (ii) in providing early warning on the timing, likely impacts and possibility of flooding to a specific urban area. Case study analysis of system performance proved extremely useful and, for two surface water flooding events observed within the Games, found to perform well within expectations.

This project provided an operational system that proved useful to SEPA and the wider community and the Glasgow Pilot was a success. As a result, a wider roll-out to other urban communities across Scotland is being considered along with an opportunity for further refinement and development of the tool guided by the user feedback. Planning will include taking account of any constraints (technical, resource and communication) associated with providing this new guidance to urban communities on surface water flooding hazard.

Key words: Flooding; surface water; precipitation; forecast; urban; model; real-time

1.0 Introduction

In urban areas, the impacts of surface water flooding can be very severe as such environments are generally densely populated and contain vital infrastructure. In recent years there have been regular occurrences of urban flooding in many parts of the UK with surface water flooding accounting for approximately one-third of flood risk from all sources (Houston et al., 2011). Within Scotland, the National Flood Risk Assessment (SEPA, 2011) estimates that around 125,000 properties are at risk of flooding from all sources and that surface water accounts for approximately 38% of the predicted impacts. Modelling, and real-time forecasting, of urban flood inundation is therefore increasingly relevant given the magnitude of potential loss and disruption.

Glasgow, in particular, has a history of surface water flooding with 5 notable events during 2002-2013. The most significant of which was in 2002 with many houses and transport infrastructure affected. This included flooding from surface water runoff, sewer flooding and flooding from other artificial drainage systems. However, it should be noted that the main focus of the current study is flooding from surface water runoff. The rainfall event in this case was estimated to be of 1 in 100 year return period (The Scottish Government, 2011) with Glasgow's East End being the worst affected district.

As part of the requirements of the Flood Risk Management Act 2009, SEPA has undertaken a national pluvial flood mapping study and is committed to increasing understanding of surface water flooding mechanisms and to developing appropriate forecasting and warning capabilities. At the outset of this research, SEPA's existing surface water forecasting capabilities included alerts for large areas based on indicative depth-duration thresholds and local hydrometeorological knowledge. No formal surface water forecasting models were in use. It is recognised that surface water flood modelling and forecasting in urban areas is challenging due to (i) potentially complex modelling requirements and (ii) convective rainfall events, which are intrinsically difficult to forecast and the dominant meteorological driver.

The CREW project aimed to assist SEPA in increasing its capabilities through developing an appropriate modelling methodology for surface water flood forecasting that could be operated in real-time. The Commonwealth Games in Glasgow (July 2014) offered a suitable opportunity to test the methodology. It provided a real situation where the risk of flooding was considered a major concern to strategic operations and where a forecasting system could be highly beneficial for the emergency response community. The remainder of this report provides a summary of the project activities, findings and conclusions based on the research objectives to:

- Review recent advances in meteorological data products (including high-resolution radar rainfall and nowcasting) to identify the best data available for pluvial forecasting in Scotland.
- Review hydrological and hydraulic models suitable for application in real-time to urban areas. This will consider innovative solutions to minimise model run-time and potential provision of flood impact information.
- Develop a pilot application of the proposed modelling methodology to Glasgow's East End, during the 2014 Commonwealth Games.
- Assess how the proposed methodology can be integrated within SEPA's existing flood forecasting platform, FEWS Scotland (Cranston et al., 2007).
- Based on experience from the Pilot Study, assess how the methodology can be rolled-out to other areas. Any barriers to transferability are to be identified.

2.0 Review of approaches for forecasting intense rainfall and surface water flooding

During the initial phase of the project two detailed review reports were produced. The first report (Golding et al., 2013) reviews recent advances in rainfall estimation and forecasting techniques with a view to identifying the best rainfall data for surface water flood forecasting. The second report (Ghimire et al., 2013a) reviews current surface water flood modelling techniques commonly used in the UK with a focus on their potential application for real-time forecasting in urban communities. These reviews were completed in 2013 and informed how the real-time pilot system for surface water flood forecasting during the Glasgow Commonwealth Games 2014 would be established. A short report (Ghimire et al., 2013b) brought together the key points that emerged from both of the detailed review reports and these are summarised in this section.

2.1 Forecasting intense rainfall likely to cause surface water flooding

- Current real-time forecasting of surface water flooding is based on rainfall threshold exceedance, coupled with use of the fixed planning maps of surface water flooding. Accuracy of real-time surface water flood forecasts is constrained by rainfall forecast accuracy. Beyond six hours ahead, Numerical Weather Prediction (NWP) provides the most accurate forecasts of rain-rate. Following recent implementation of the United Kingdom Variable grid (UKV) model with a 1.5km grid, NWP is often very skilful at predicting maximum rainfall accumulations. However, the timing and location are subject to substantial uncertainty (typically one hour and 25km respectively).
- The remaining forecast uncertainty, particularly in the location and timing of convective rainfall, makes it necessary to always base management decisions on probabilistic rainfall forecasts.
- At very short lead-times, the Short Term Ensemble Prediction System (STEPS) nowcast provides useful radar-rainfall extrapolation ensemble forecasts, blended with the deterministic UKV model up to six hours ahead.
- At longer lead-times, ensemble NWP is the preferred forecasting approach. The existing Met Office Global & Regional Ensemble Prediction System – Regional (MOGREPS-R) 12km grid ensemble has recently been replaced by the Met Office Global & Regional Ensemble Prediction System – United Kingdom (MOGREPS-UK) 2.2km ensemble, which was trialled in 2012. Substantially improved results have been obtained. The information from this ensemble is already being delivered to SEPA as part of the Scotland-wide MOGREPS-R replacement, albeit at a reduced resolution of 12km to conserve data volumes.
- Initialisation, calibration and verification of forecasting systems depend on good quality rainfall observations. Currently, significant parts of Scotland are under-observed due to (i) sparseness of the real-time reporting raingauge network, (ii) distance from a weather radar and other factors influencing radar's ability to estimate ground-level rainfall, and (iii) the hilly and remote nature of the terrain that makes extensive ground monitoring difficult.
- Improvements to rainfall observation across Scotland will be enabled by work in progress to increase the use of real-time polling of SEPA's tipping bucket raingauge network and to complete the UK radar network upgrade. Further work is required to optimise the use of the new radar

technology, particularly its dual-polarisation capability, and to combine raingauge and radar observations more effectively.

- A blended precipitation ensemble forecast will be introduced in October 2013, combining the 2km STEPS extrapolation forecasts with the MOGREPS-UK 2.2km forecasts. This will provide the best probabilistic forecast up to 36 hours ahead on a 2km grid.
- An hourly precipitation forecast using an enhanced data assimilation method will be implemented at the Met Office in 2015/6. Based on experience for a small area of Southern England in 2012, it is anticipated that this will provide a further improvement in rainfall forecast accuracy. However, spatial uncertainty will still exceed 10km and ensemble processing will remain a key part of the forecasting chain.

2.2 Surface water flood modelling and forecasting for urban communities

- Developing real-time flood forecasting for operational use means that model run-time should be short enough to allow the production of longer lead-time ensemble forecasts required to facilitate effective mitigation actions. Because of this, detailed flood modelling combining both surface runoff and the underground sewerage network system - which demand longer run times - will not prove feasible. Instead, an estimate of the sewer capacity is required to be made to take into account the amount of flow that is expected to enter the sewerage network during extreme events. Even then, 2-D hydraulic modelling of surface water flooding remains infeasible to meet the real-time forecast run-time requirements at the present time. Although advances in computing are expected to make this possible in the future, the sustained investment required to support a robust and verified operational system should not be underestimated.
- A further consideration for real-time application is the need for continuous running of a model, involving maintaining model states (e.g. antecedent conditions of water volumes) across all time-steps up to the time the forecast is made. Not all inundation models originally implemented for design and planning are well suited in this respect for real-time application, and may require considerable development and restructuring of the software. Also, their inputs may relate to an “effective rainfall” design storm profile and may not include an explicit space-time representation of runoff production and water loss accounting. As a result, areas of inundation are not necessarily drained and fully evacuated in the aftermath of a surface water flooding episode, remaining inundated indefinitely.
- The above considerations indicate that real-time surface water flood inundation modelling is still in a research phase and not suitable for development and use in the Commonwealth Games 2014 Pilot. Of the candidate surface water inundation models reviewed, only ISIS-FAST is identified as fast enough to run in real-time but will not be considered for use in the Pilot as it requires significant further development, testing and verification for use as an operational tool.

2.3 Surface water flood forecasts

- Real-time surface runoff forecasts can be provided by the Centre for Ecology & Hydrology’s (CEH’s) Grid-to-Grid (G2G) distributed hydrological model. G2G is currently used operationally in real-time across Scotland by the Scottish Flood Forecasting Service with a focus on providing guidance on fluvial flooding over the next few days. Surface runoff in the model is routed through the river network to obtain fluvial flood forecasts and is also available to be configured as an output to support forecasting of surface water flooding.

- Existing approaches for real-time surface water flooding alerts are based on rainfall threshold exceedance methods which identify in map form areas at risk. G2G offers a potential advance on such approaches, through bringing in dependence on surface cover, soil properties and antecedent wetness condition.
- Under the Natural Hazards Partnership Surface Water Flooding initiative, a case study has pointed to the potential value of G2G for surface water flooding alerts and further studies are ongoing. It is recommended the G2G model be applied to the Commonwealth Games Pilot and be guided by these additional ongoing case study investigations.
- In contrast to G2G, the more detailed hydraulic model JFlow+ has been applied for planning and design purposes under the Glasgow Pluvial Flood Mapping (GPFM) project and under the Regional Pluvial Flood Hazard (RPFH) project. An outcome of these projects are datasets on surface water flooding providing detailed information on flooding associated with design storms of varying severity/rarity. Exploratory work is to be done, in the project's implementation phase, on linking these off-line datasets with G2G to better resolve the real-time G2G surface water runoff forecasts.
- Scoping study work is underway between CEH and SEPA on combining the G2G flooding hazard footprint with impact datasets; related work is also ongoing between CEH and the Health and Safety Laboratory under the Natural Hazards Partnership. The outcome of this work is to be pulled through to this CREW project (where possible) so as to produce surface water hazard impact maps of practical relevance to decision-making during the Commonwealth Games.
- Further work is required to determine how best to present the surface water flooding forecasts and any impact information within FEWS Scotland, and communicate to responders, particularly bearing in mind the spatial uncertainty in the input rainfall data.
- In order to provide an adequate estimate of the probability of flooding, it will be necessary to run the G2G model with rainfall inputs from the blended ensemble members. If necessary for efficiency purposes, a dedicated small domain version of G2G should be run for just the Glasgow area. This should not have any undesirable impact, given that the collection area for surface water floods is usually very small.

3.0 Glasgow Commonwealth Games Pilot Study

SEPA formed and chaired a Steering Group of key responders in Glasgow including the City Council, Transport Scotland, Scottish Water, the Scottish Government and those involved in the Commonwealth Games organisation. The Steering Group was formed to ensure the Pilot Study would meet the needs of end-users and to set realistic expectations for the operational outputs. Following the review stage, a meeting with the Steering Group identified the key requirements of the operational responders and, based on the findings of the reviews, agreed the outline plan for the Pilot Study.

This section provides a summary of the key user requirements, an outline of the proposed pilot, details of the various components of the actual pilot and closes with experiences from using the system during the Commonwealth Games.

3.1 Overview of needs and outline plan for the Pilot Study

The main needs of the Pilot Study identified by the Steering Group were:

- Focus on 6 to 24 hour lead-times to enable proactive preparations: 12 hours was seen as a "critical" forecast horizon.
- Guidance on event timings, locations, possible impacts & severity.
- A "stand-down" message when the event is over or the risk-level reduced was seen as crucial.
- Challenge to balance the user-requirements against the scientific and operational capabilities.

Following the reviews, the Grid-to-Grid (G2G) model was selected to provide the basic framework for surface water flood modelling. Testing of the methodology was to be undertaken through application of the G2G model to the Glasgow Commonwealth Games Pilot Study, supported by further studies that are being undertaken through the Natural Hazards Partnership Surface Water Flooding initiative. The domain of application would be a 10 by 10 km grid covering the East End of Glasgow. Prior to implementation for the Pilot Study area, exploratory work would also examine whether outputs from detailed surface water flooding models used for planning and design (e.g. JFlow+) could be linked to G2G to better resolve the real-time G2G surface water runoff forecasts.

The G2G model would be run with rainfall inputs from both the ensemble STEPS nowcast system and the blended precipitation ensemble forecast, combining the 2km STEPS radar extrapolation forecast with the MOGREPS-UK 2.2km Numerical Weather Prediction model forecast. The study would also examine how to best present and communicate to responders the risks and impacts of surface water flooding, whilst taking on board the spatial and temporal uncertainty in the forecast rainfall. The resulting guidance on surface water flooding would aim to support practical decision-making during the Glasgow Commonwealth Games 2014.

3.2 Rainfall forecasts

For the Glasgow Pilot Study, the Met Office provided blended, control (unperturbed) and 24 member ensemble (perturbed) nowcasts and forecasts of 15 minute rain accumulations with ranges of up to 7 and 32 hours respectively, four times daily (nowcast origin times: 05:30, 11:30, 17:30 and 23:30 GMT; forecast reference times: 01:00, 07:00, 13:00 and 19:00 GMT). The control nowcast and forecast were blends of a STEPS-based (Short Term Ensemble Prediction System, Bowler et al., 2006;

Seed et al., 2013) extrapolation nowcast, and a recent forecast from the variable resolution 1.5km configuration of the Met Office's Unified Model (UKV). The influence of the extrapolation nowcast relaxes to zero at a range of 7 hours. The ensemble nowcast and forecast are blends of the extrapolation nowcast and a recent MOGREPS-UK (Met Office Global & Regional Ensemble Prediction System, Golding et al., 2014) 2.2km NWP ensemble forecast.

The blending of these nowcasts and forecasts exploits a scale decomposition framework and time series of synthetic rainfall fields (noise or pseudo-random numbers that look like radar-inferred or NWP forecast rainfall), developed for STEPS to produce seamless, high resolution (2 km grid length), composite precipitation forecasts. Scale decomposition allows these components to be combined on a hierarchy of spatial scales in a near optimal way, using weights that reflect the relative skill of the nowcast and NWP forecasts at these scales. The noise enables their seamless combination, accommodating disparities in the phase and amplitude of predicted rainfall. In the MOGREPS-UK-based blended ensembles, the perturbations introduced by the noise are restricted to scales below ~100 km. This is because neighbourhood-based calibration techniques (Roberts and Lean, 2008) demonstrate that sampling the MOGREPS-UK ensemble over a 100 km neighbourhood surrounding a given forecast grid point already produces well calibrated, grid-scale probabilistic forecasts (Roberts, 2013).

Currently, the ensemble size of MOGREPS-UK is restricted to 12 members by available supercomputer capacity. The blended ensemble generation techniques outlined above allow an additional 12 members to be produced at relatively low cost. These extra forecast scenarios produce better calibrated probabilistic forecasts of rain accumulation at the grid (2 km) scale and hence enable better calibrated warnings for both pluvial and fluvial floods. Figure 1 compares the reliability of 12 member MOGREPS-UK ensemble precipitation forecasts of hourly rain accumulation with that of equivalent, 24 member, blended ensemble precipitation forecasts of the same quantity. The verification period is July 2012. Approximately 400 Met Office raingauges were used as the verification reference. This comparison shows the 12 member MOGREPS-UK ensembles to be under-spread at the grid scale. The additional 12, blended forecast scenarios are seen to correct for much of this lack of spread.

(a) (b)

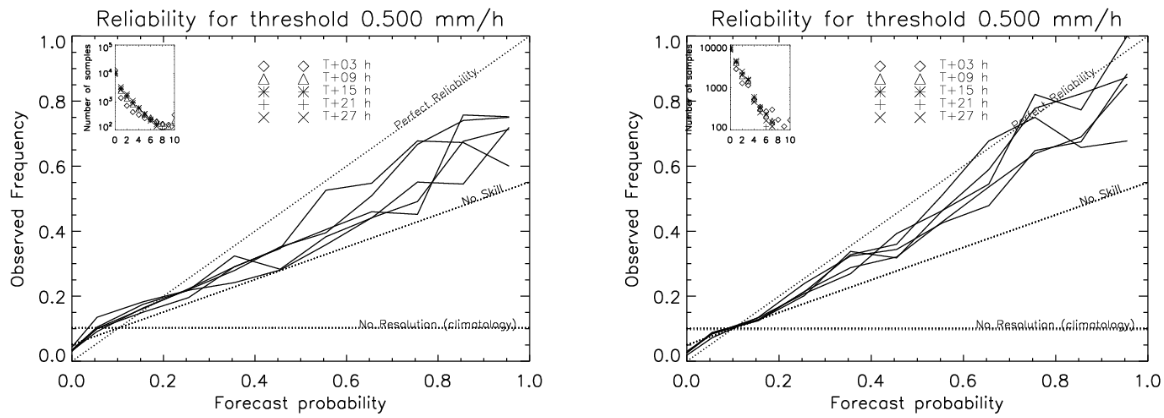


Figure 1 Comparative evaluation of the reliability of ensemble forecasts of hourly rain accumulation from (a) a 12 member MOGREPS-UK ensemble, and (b) 24 member MOGREPS-UK-based blended ensemble incorporating an extrapolation nowcast. The verification period is July 2012 and approximately 400 Met Office raingauges were used as the verification reference.

To support the Pilot Study, a real-time datafeed of the 24 member blended ensembles (32 hour lead-time) and nowcast ensembles (7 hour lead-time) were delivered from the Met Office to SEPA. These were provided as 2 km resolution 15 minute rainfall accumulations on a 22 km by 22 km domain over Glasgow. Note that blended ensemble forecasts for the four forecast reference times (01:00, 07:00, 13:00 and 19:00 GMT) should use MOGREPS-UK data from forecast origins of 21:00, 03:00, 09:00 and 15:00 GMT respectively. Forecast data for the first 4 hour period of the MOGREPS-UK forecast is not sent as it takes around 5 to 6 hours for the MOGREPS-UK data to become available. Although nowcasts are potentially available every 15 minutes, only 4 a day were selected for use in the Pilot Study. These were chosen to give updates to the pilot system outputs at mid-points between the outputs based on the blended ensemble forecasts.

3.3 G2G model application

The Grid-to-Grid model, or G2G, is a distributed grid-based rainfall-runoff and routing model developed by CEH (Moore et al., 2006, 2007; Bell et al., 2009). A schematic of G2G is presented in Figure 2 by way of background.

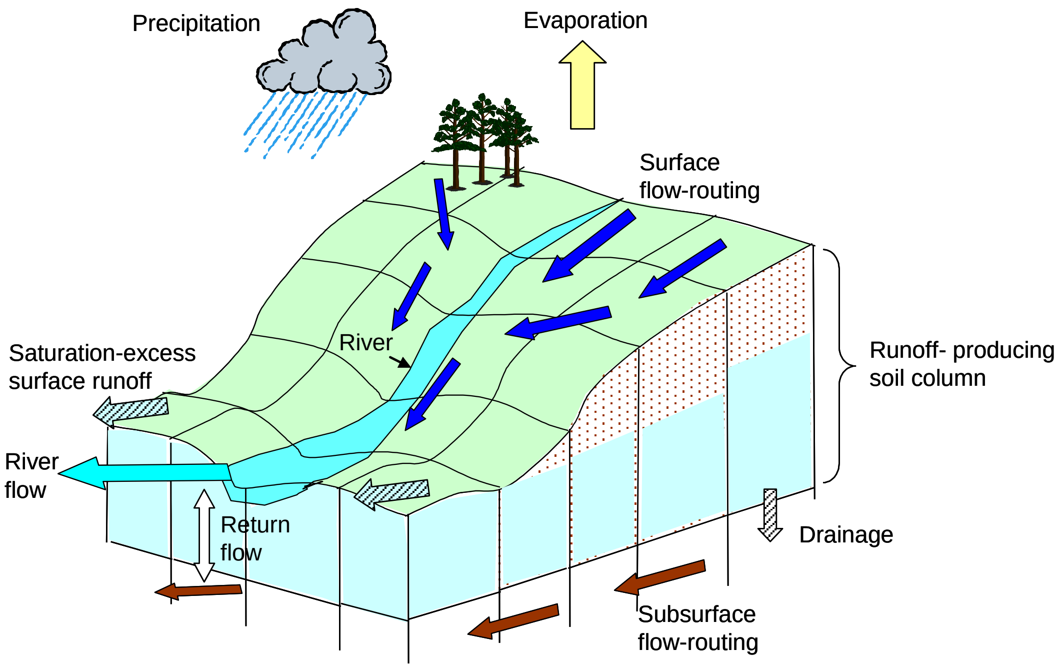


Figure 2 Schematic of the Grid-to-Grid Model

G2G is formulated to represent spatial variability in catchment response and to make full use of spatially-distributed rainfall data derived from networks of radars and raingauges, nowcasts and weather model forecasts. The model employed operationally across Scotland, England and Wales is configured to run on a 1 km grid and for a time-step of 15 minutes. Spatial datasets (e.g. terrain, soil/geology, land-cover) are used to support its configuration and parameterisation.

G2G runs at a 15-minute time-step to align with national hydrometric data availability and is currently configured at a 1km resolution. Gridded outputs from G2G include estimates of river flow (m^3s^{-1}) and soil moisture (a deficit in mm or a saturation percentage) but, importantly, also includes surface runoff as an average water depth over a grid square in mm which can be used to assess the surface water flooding hazard.

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. More specifically, surface water generation is represented by a soil- and slope-controlled probability-distributed storage-capacity scheme modified by land-cover (e.g. urban) effects. Continuous soil moisture accounting establishes “antecedent conditions” affecting subsequent runoff generation.

G2G is already used operationally for countrywide forecasting of fluvial flooding to support the fluvial elements of the Flood Guidance Statement (FGS): across Scotland by the Scottish Flood Forecasting Service (SFFS) (Cranston et al., 2012) and across England and Wales by the Flood Forecasting Centre (FFC) (Price et al., 2012).

A Performance Summary is provided for both SFFS and FFC applications of G2G, reporting in a pdf document for each gauging station, an assessment of model accuracy in simulation- and forecast-mode through hydrograph displays and a variety of performance statistics. The assessment covers ~250 gauging stations and 4 years of record in Scotland and ~900 gauging stations and 4 years of record in England & Wales. Although these assessments relate to fluvial flows, they do provide an indirect indication that the surface runoff – prior to translation over land and through river channels – may be reasonably well represented at the 1km^2 grid-scale of the model. Also, the water accounting procedure that underpins the surface runoff production scheme has a mature pedigree developed over many years, as part of G2G and the related PDM catchment rainfall-runoff model (Moore, 1985; Moore, 2007) used within FEWS Scotland and the National Flood Forecasting System (NFFS) across England & Wales.

Using dynamic gridded surface runoff estimates from G2G can provide a potentially significant step forward in assessing the surface water flooding hazard footprint, compared to existing operational methods primarily based on rainfall depth. Furthermore, information from detailed flood inundation maps can be exploited to provide impact assessments and, in turn, provide a real-time impact and risk assessment of surface water flooding. This approach has been progressed by CEH as a Natural Hazards Partnership (NHP) activity with co-funding from the Environment Agency and from CEH(NERC) under its National Capability programme. In collaboration with the Health and Safety Laboratory (HSL) in relation to impacts, and with the Met Office in relation to gridded rainfall forecasts in deterministic and ensemble form, a Surface Water Flooding Hazard Impact Model (SWF HIM) has been developed.

As a first pass the SWF hazard footprint can be assessed by comparing the dynamic G2G surface runoff forecasts to static exceedance thresholds (e.g. 13.5 mm in 3 hours). In order to assess potential impacts in real-time, detailed offline flood inundation maps - such as the updated Flood Map for Surface Water (England & Wales) - can be utilised by equating the G2G surface runoff to the “effective rainfall” scenarios used to form the maps (e.g. 100 year return period, 3 hour duration storm). In this way an offline “impact library” can be pre-calculated for the detailed flood inundation maps and a dynamic impact assessment can be made by identifying the maximum "effective rainfall" scenario exceeded by the G2G surface runoff forecasts for each pixel. Repeating this for each ensemble member allows the likelihood of any impact also to be calculated. In this way, a SWF risk assessment can be made which ties in with the established Flood Guidance Statement methodology that links likelihood and potential impact through a Flood Risk Matrix to give a severity level of flooding risk. Further NHP development and testing with a view to near-operational trialling over England & Wales is planned during 2015/16: recent progress is reported in Cole et al. (2013, 2014).

A similar approach to the NHP SWF Hazard Impact Model was applied to the Glasgow Pilot Study and the following sub-sections provide a more detailed explanation.

3.4 Methodology for impact assessments and outputs used in the Glasgow Pilot

As outlined previously, G2G does not provide detailed inundation or impact modelling. To overcome this, detailed offline inundation maps were used. Within Glasgow, there were several potential sources of detailed inundation maps such as those produced under the Glasgow Pluvial Flood Mapping project. However, a driver of the project was to select a methodology that could potentially be applied to other urban communities across Scotland. Therefore the static inundation and impact assessments from SEPA's Regional Pluvial Flood Hazard (RPFH) maps were selected for use in the Pilot Study.

The Regional Pluvial Flood Hazard (RPFH) inundation maps were released in early 2014 as part of the national surface water flood mapping requirement of the Flood Risk Management (Scotland) Act 2009. These maps were formed from the three sources listed below.

1. National surface water study as part of the National Flood Risk Assessment. Uses ISIS-Fast.
2. Regional surface water study for selected regions. Uses JFlow+ (JBA Consulting & Mott MacDonald, 2013).
3. Scottish Water sewer flooding assessments (under Section 16 of the Flood Risk Management Act). Based on InfoWorks CS.

It should be noted that although the Scottish Water sewer flooding assessments were included in the RPFH flood outline maps at a late stage, only the national (ISIS-Fast) and regional (JFlow+) maps were used by SEPA for calculating the static impact maps.

For the Glasgow case study area (and indeed for most urban areas of concern across Scotland), the regional study based on JFlow+ is the primary mapping source. The Digital Terrain Model (DTM) used by JFlow+ was constructed from 2m LiDAR and 5m NEXTMap data with ground levels raised by 0.3m to represent buildings (2m resolution was available over the pilot area). Five different rainfall return periods (10, 30, 50, 100 and 200 years) for 2 different storm durations (1 and 3 hours), as well as two climate change (cc) rainfall scenarios (30+cc = 30 year + 20% and 200+cc = 200 year + 20%) were used. The gridded rainfall depths for the rainfall scenarios were derived on a 5km grid using the Centre for Ecology & Hydrology's Flood Estimation Handbook (FEH) Rainfall Depth-Duration-Frequency (DDF) model (Faulkner, 1999).

In order to calculate the "effective rainfall" used as input to the JFlow+ model, a percentage runoff of 55% was assumed for "rural" areas and 70% for "urban" areas. In addition, for "urban" areas a constant allowance was made for losses to the drainage system equal to the 5 year return period rainfall. To derive a realistic hyetograph over the storm duration, the FEH 50% summer rainfall profile was used as this best represents the short periods of high intensity rainfall associated with convective storms. The Land Cover Map 2007 (LCM2007; Morton et al., 2011), also from the Centre for Ecology & Hydrology, was used to classify the base DTM pixels as "urban" (LCM2007 classes urban and suburban) or "rural". The urban/rural split for the pilot area is presented in the right-hand side of figure 3 and the corresponding hyetographs for a particular 5km rainfall grid are given on the left-hand side. Examples of the rural and urban 3 hour duration, 10 year return period effective rainfall totals are given in Figure 4 together with a 1km average calculated using the urban/rural split – this is on the same 1km grid as the Grid-to-Grid model**.**

Once the JFlow+ maps were produced, areas with flood depths of less than 0.1m were removed as these were judged to be of low risk and within the associated uncertainty of the modelling approach. SEPA then undertook a static impact assessment of the JFlow+ maps for each "effective rainfall" scenario (for the 3 hour duration only) against the following six different receptors:

Population (number of properties affected per 1km pixel: e.g. 1-50, 51-100)
Community Services (point locations)
Utilities (point locations)
Commercial Properties (point locations)
Railway (lines of affected railway)
Roads (lines of affected roads).

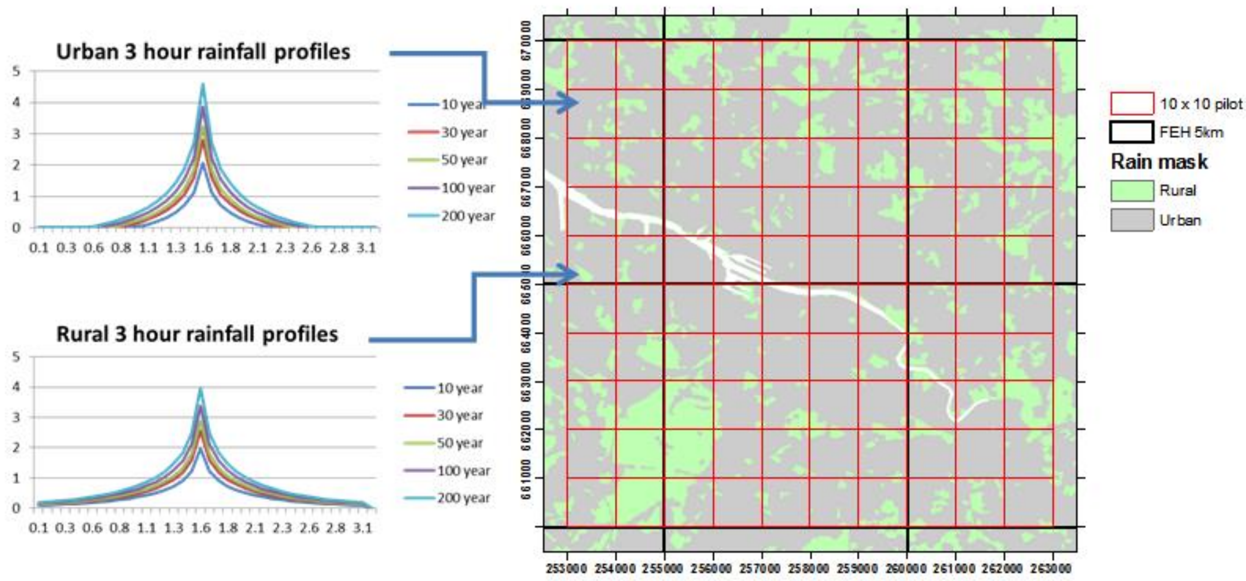


Figure 3 Left: Example of the "effective rainfall" hyetographs for "urban" and "rural" pixels. Right: "urban" and "rural" pixels highlighted. Black grid is the 5km rainfall grid (all rainfall profiles within this grid are the same). Red grid is the 10 by 10 km area for the Glasgow Pilot Study.

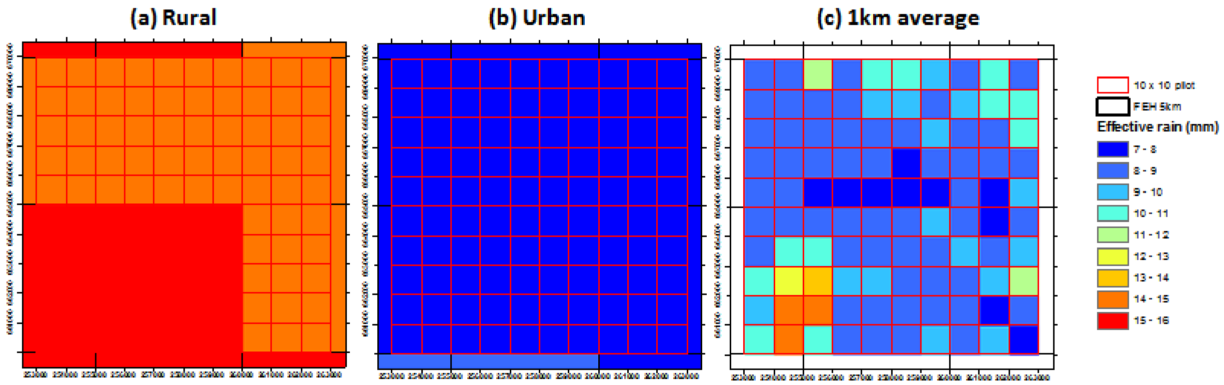


Figure 4 Effective rainfall maps for the 10 year return period, 3 hour duration: (a) for rural 2m pixels, (b) for urban 2m pixels, (c) average 1km effective rainfalls using the urban/rural split presented in Figure 3.

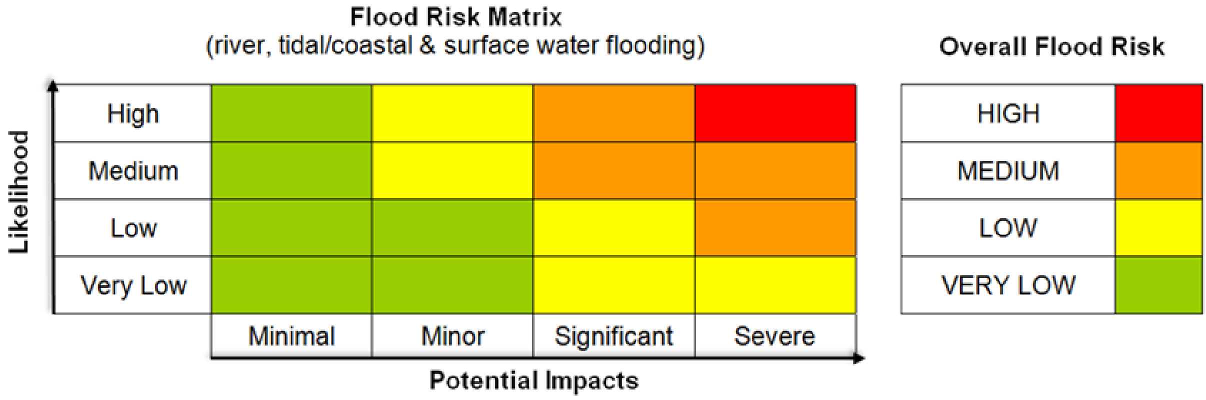


Figure 5 The national Flood Risk Matrix used by SEPA for the Flood Guidance Statement.

The Scottish Flood Forecasting Service uses a national Flood Risk Matrix approach, as shown in figure 5, combines potential impact with likelihood to assign an overall risk level. As part of this approach, there is a national description of what the different levels of potential impact are. For the Pilot Study it was necessary to create 1km grid-cell impact definitions that could then be applied to the six receptors. The impacts were grouped into people and property impacts (population, community services, utilities, commercial properties) and transport (railway and road). Transport was considered as a separate category, since impacts in any one grid-cell are likely to cause significant disruption across a wider area. This grouping of receptors was important as it reduced the number of impact maps that a user may have to interpret in a pressurised, time-critical operational system. Table 1 summarises the categories of impact severity, the associated definition of the impact within a 1km grid-cell for the Glasgow domain, and national descriptions of the impact and expected partner response.

For each of the seven rainfall scenarios, an associated gridded "impact classification map" for each receptor was calculated offline on the FGS impact scale (minor, significant and severe) using the definitions in Table 1. Then the seven "impact classification maps" were simplified to one "minimum effective rainfall map" for each impact level: this simply contains the lowest effective rainfall threshold that gives that level of impact (note railways and roads only had significant levels of impact). An example, breaking down the calculation steps for the population receptor, is given in Figure 6. Furthermore, the “minimum effective rainfall maps” for each receptor could be combined with other receptors (e.g. the people and property grouping) by keeping the minimum effective rainfall for each pixel across the different receptors. This approach allows offline compilation of an “impact library” of minimum effective rainfall thresholds for each receptor (or group of receptors) and severity level which can then be compared with the real-time forecast surface runoff accumulations from the Grid-to-Grid model. The six minimum effective rainfall threshold grids used in the final “impact library” are presented in Figure 7: People and Property x 3 (minor, significant, severe), railways, roads and combined railways and roads (transport).

It should be noted that the 1km grid-cell impact definitions were developed specifically for the Glasgow Pilot Study and would need to be reassessed if applied to other urban areas in Scotland. There was some manual checking of the offline impact assessments over Glasgow and comparison with local knowledge. In particular there was a site visit, led by a local expert from Scottish Water, which identified the London Road as a particular hotspot for surface water flooding, even for relatively low rainfall totals. However, this area was only mapped as flooding for the 200 year + cc rainfall scenario, possibly because of the 0.1m threshold applied to the flood maps. Therefore a manual edit was applied to this area to give a lower effective rainfall accumulation. Some form of manual checking of the impact assessments is advisable for any new urban areas where such an approach is used.

Table 1 National impact descriptions used in the Flood Guidance Statement and associated 1km grid-cell impact thresholds for the Glasgow Pilot Study.

Impact category	National description	Expected National Partner Response	Glasgow threshold per grid cell	
			People and property	**Transport**
Minimal	Generally no impact, however there may be: • Isolated and minor flooding of low-lying land and roads	Business as usual		
Minor	• Localised flooding of land and roads • Localised flooding affecting individual properties • Localised disruption to key sites on floodplains • Local disruption to travel	Single agency operational response	1-100 residential properties 1-2 community services 1-2 utilities 1-20 commercial properties	
Significant	• Flooding affecting parts of communities • Damage of buildings/structures is possible • Possible danger to life due to fast flowing/deep water/ wave overtopping/ wave inundation • Disruption to infrastructure • Small-scale evacuation of properties may be required	Multi-agency response likely to be needed at tactical level. SGoRR* may be considered.	1-100 residential properties > 2 community services > 2 utilities > 20 commercial properties	> 5m road > 5m railway
Severe	• Widespread flooding affecting whole communities • Collapse of buildings/structures is possible • Danger to life due to fast flowing/ deep water • Widespread disruption or loss of infrastructure • Large scale evacuation of properties may be required	Multi-agency strategic response likely at SCG* level or regional level. Mutual aid likely with perhaps national co-ordination. SGoRR* convened.	> 100 residential properties	

*SCG: Strategic Co-ordinating Group. SGoRR: Scottish Government Resilience Room

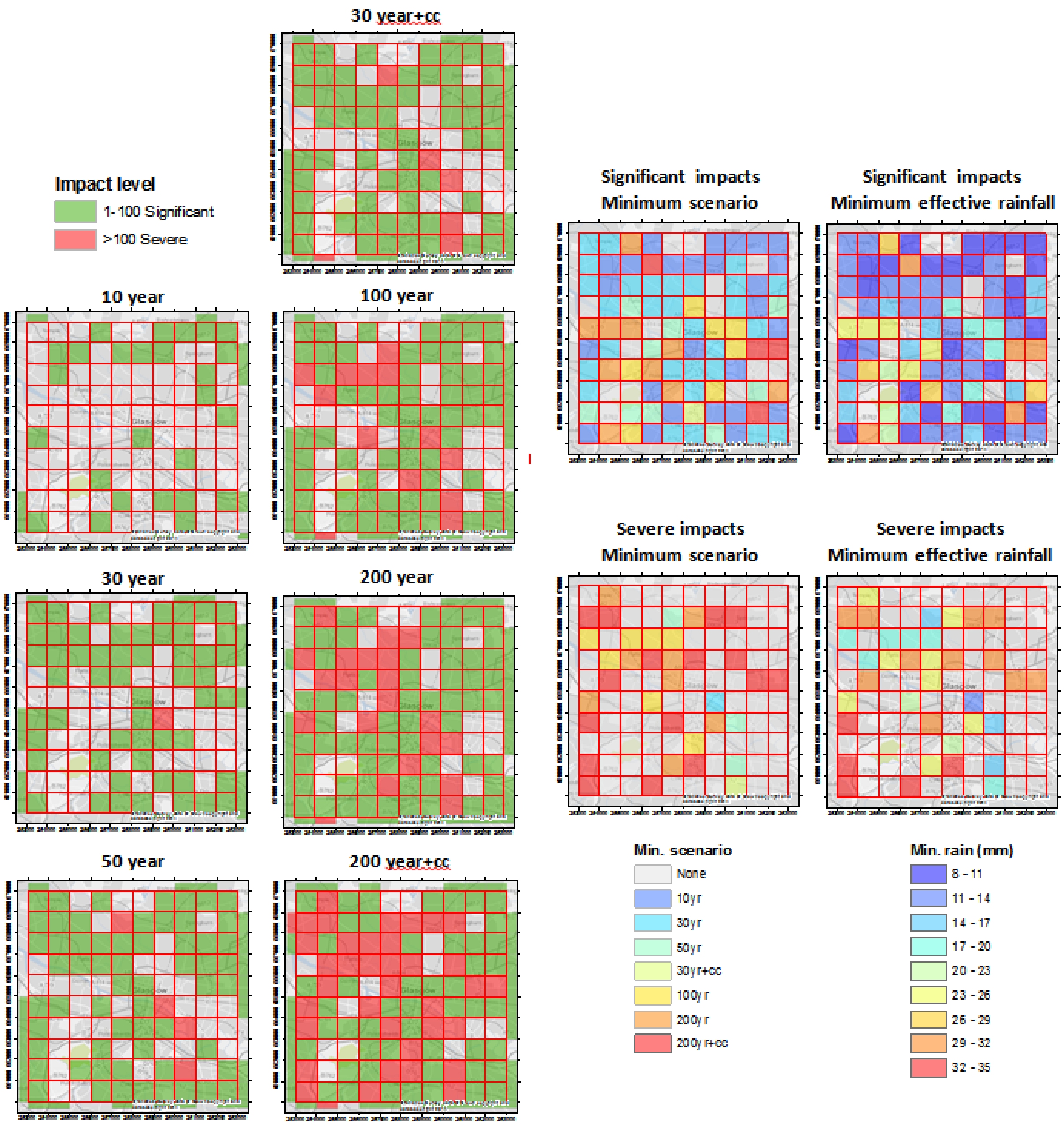


Figure 6 Offline impact calculations for the population receptor. Left-hand side: impact classification for each rainfall scenario. Right-hand side: minimum rainfall scenarios and associated effective rainfall for attaining the significant (top row) and severe (bottom row) levels of impact.

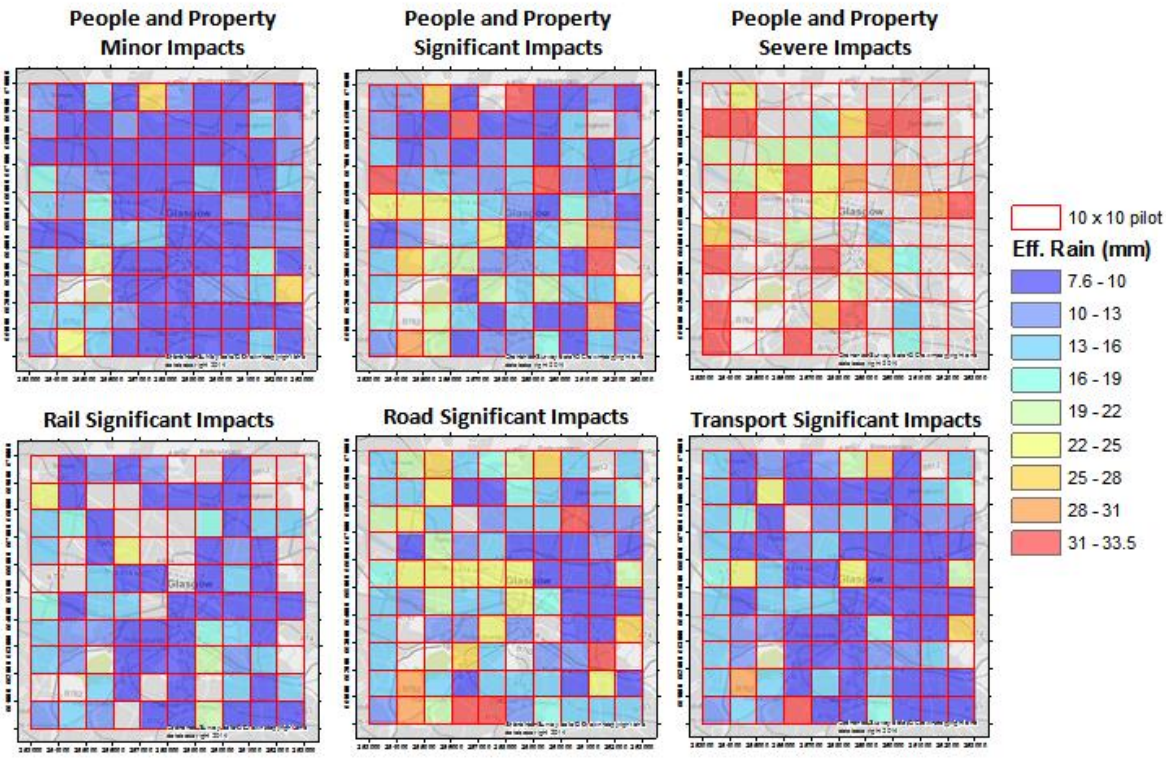


Figure 7 The six minimum effective rainfall threshold grids used in the final "impact library". Top row: People and Property x 3 (minor, significant and severe impacts). Bottom row: railways, roads and combined railways and roads (transport) – all significant impacts.

3.4.1 Display of probabilistic model output

A primary operational output during the Pilot is a risk level assessment of surface water flooding. In order to achieve this, the operational hydrometeorologist must have enough information and transparency to understand how the automated surface water flooding forecast and impact products are constructed without being overwhelmed by information. Therefore novel methods for presenting the wealth of ensemble forecast model and impact output were required. A key approach to this was to summarise outputs over a forecast time-horizon and, for the impact assessments, noting that the "likelihood" classifications in the Flood Risk Matrix (figure 5) are defined using the following probability of occurrence bands: very low <20%; low 20-40%; medium 40-60%; high 60% or greater.

A generic illustration of the approach is presented in figure 8 for a forecast starting at time *T*. The process is, for each ensemble member, calculate a 15 minute sequence of 3 hour accumulations (surface runoff or rainfall) and note, for each pixel, if the accumulation exceeds the threshold under consideration. When completed for all ensemble members, a grid of threshold exceedance probabilities can be calculated and displayed. This can be applied to the whole forecast as a useful overview and also to portions of the forecast to understand how the risk evolves in time. The illustration shows how the exceedance probabilities over the whole forecast must be equal to or greater than the exceedance probabilities for any of the sub-parts of the forecast. A 3 hour accumulation is used as this is the duration employed in deriving the offline “impact library”.

The threshold exceedance probability approach can be applied to universal rainfall and surface runoff thresholds or to the impact library. An overview of the operational gridded products produced is shown in Figure 9.

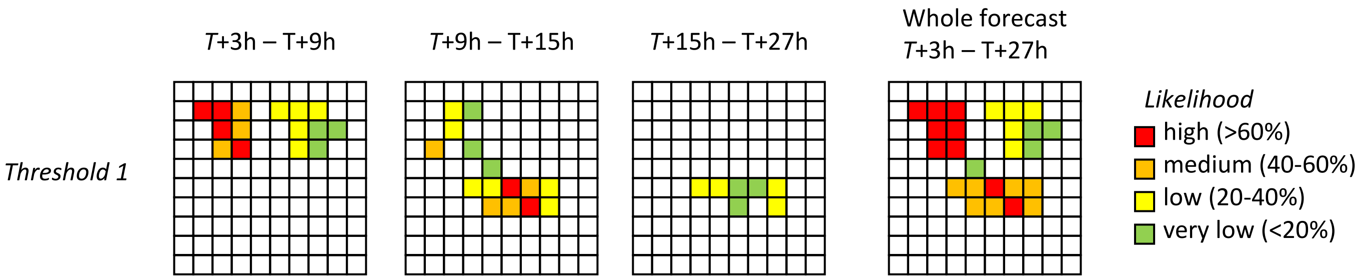


Figure 8 Illustration of how gridded maps of threshold exceedance probabilities can be presented for part- and whole-periods over the forecast horizon.

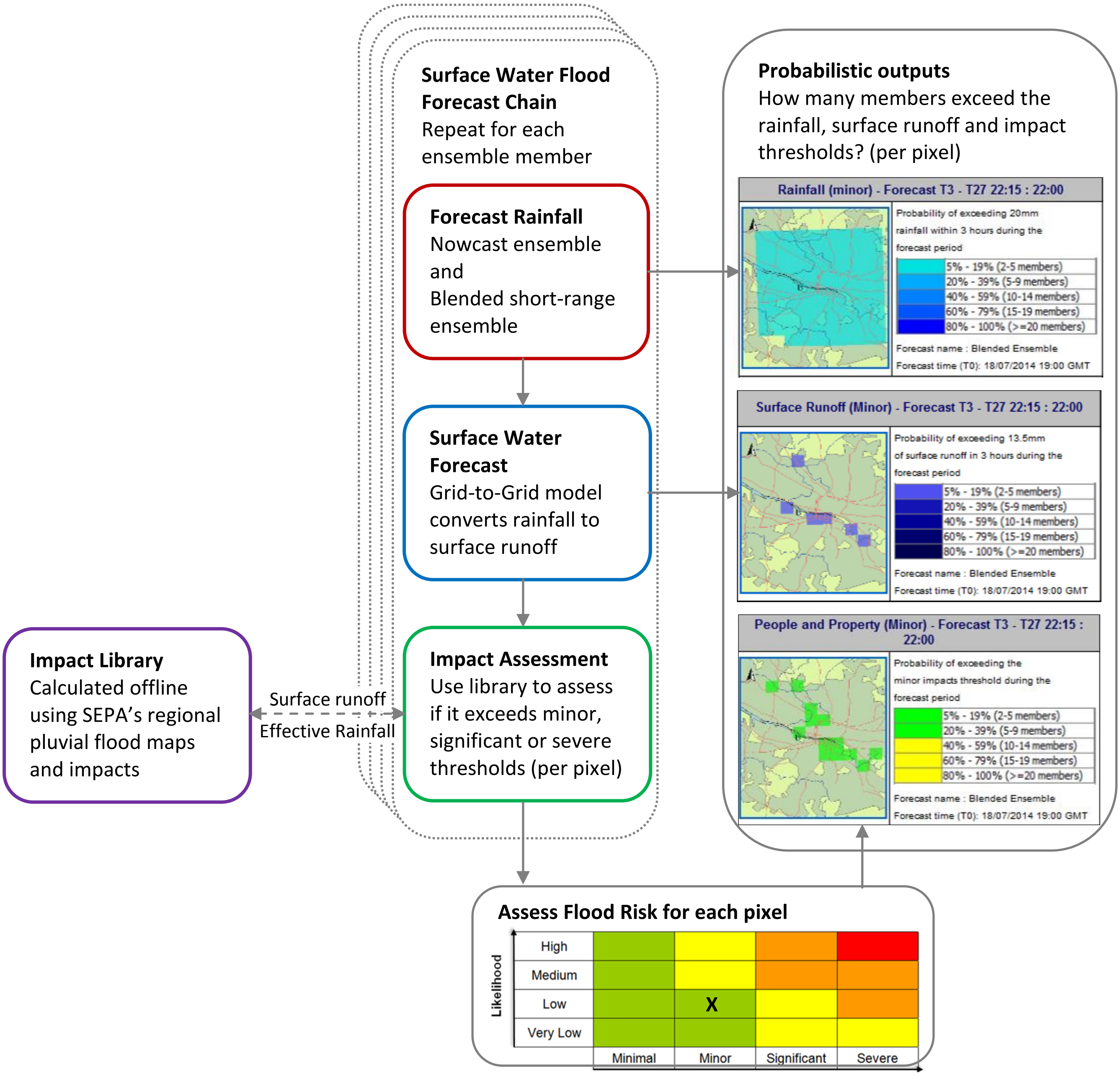


Figure 9 Overview of the surface water flood forecasting chain, impact assessments and examples of the probabilistic outputs.

Further details of the gridded products are given below along with an additional time-series chart that aims to convey some of the variability between ensembles. Note that a lower threshold of 5% is applied for displaying exceedance probabilities meaning that at least two ensemble members has to cross the threshold. This serves to reduce the sensitivity of the model outputs to low likelihood or outlier events.

Rainfall: gridded

Probability of exceeding 20mm in 3 hours at any time within the whole forecast and the 6 hour forecast windows (e.g. T+3 to T+9, T+9 to T+15). Nominally associated with minor impacts.

Surface runoff: gridded

Probability of exceeding 13.5mm (nominally minor impacts) or 16mm (nominally significant impacts) in 3 hours at any time within the whole forecast and the 6 hour forecast windows.

Transport impacts: gridded

Roads. Probability of exceeding the significant impacts to roads (>5m flooded) threshold grid from the impact library in 3 hours at any time within the whole forecast and the 6 hour forecast windows. Colour-coded to Flood Risk Matrix (i.e. <40% yellow – low risk, >40% amber – medium risk).

Railway. Probability of exceeding the significant impacts to railway (>5m flooded) threshold grid from the impact library in 3 hours at any time within the whole forecast and the 6 hour forecast windows. Colour-coded to the Flood Risk Matrix.

Transport (Roads and Railway). Probability of exceeding the significant impacts to transport (>5m roads ***or*** railway flooded) threshold grid from the impact library in 3 hours at any time within the whole forecast only (not for 6 hour forecast windows). Colour-coded to the Flood Risk Matrix. **One of two main outputs that inform the Glasgow Daily Surface Water Flood Forecast discussed later.**

People and Property impacts minor, significant severe: gridded

Exceedance probability grids produced separately for minor, significant and severe impact levels.

Probability of exceeding the minor/significant/severe impacts to people and property threshold grid from the impact library in 3 hours at any time within the forecast period. Colour-coded to the Flood Risk Matrix.

People and Property impacts, overall risk: gridded

For the whole forecast only (not for the 6 hour forecast windows), the maximum risk (as per the Flood Risk Matrix) from the minor, significant and severe exceedance probability grids is displayed for each pixel. Colour-coded to the Flood Risk Matrix. **One of two main outputs that inform the Glasgow Daily Surface Water Flood Forecast discussed later.**

Surface runoff – time-series

The gridded outputs show collated information across all ensemble members. To give some insight into the ensemble spread, a surface runoff time-series display is produced showing the maximum 3 hour surface runoff accumulation in any grid-cell for each ensemble member over each time-step of the whole forecast. These plots include the surface runoff accumulation thresholds of 13.5 and 16mm used in the gridded outputs as a reference.

3.5 Implementation within SEPA's operational FEWS system

The model outputs outlined in Section 3.4.1 were produced operationally as web reports developed by Deltares (contracted directly by SEPA) utilising the Delft-FEWS (Flood Early Warning System, Werner et al. 2013) with its application here referred to as FEWS Glasgow. The G2G model already runs routinely within FEWS Scotland and available to provide daily model states files to FEWS Glasgow. The G2G Glasgow model was configured to run at a 15 minute time-step on a 1km grid over a 22km by 22km area of southwest Scotland to minimise any boundary effects on the 10km by 10km area of the Pilot Study. Observed gridded rainfalls based on telemetry raingauges within the vicinity of the Pilot Study area are used as input to the G2G Glasgow model for the period between the daily G2G Scotland states file and the start of a G2G Glasgow forecast.

Section 3.2 described the two different ensemble rainfall forecast products used to generate the FEWS Glasgow outputs: (i) 24 member short-range blended ensembles (out to 32 hours, 4 forecasts per day); (ii) 24 member nowcast ensembles (out to 7 hours, four forecasts per day). These are provided as 15 minute rainfall accumulations on a 2km grid. For the short-range blended ensembles, model outputs are only produced out to 27 hours. This choice aims to mitigate effects of increasing uncertainty in forecasting convective events with increasing lead-time while maintaining 24 hours of useable forecast lead-time after the delivery and processing of the forecast. Most of the three hour delay is attributable to processing and data transfer from the Met Office supercomputer to SEPA; because of the small Glasgow model domain the FEWS Glasgow processing time at SEPA is approximately 2.5 minutes. Gridded outputs are produced for the whole forecast period (T+3 to T+27 hours) and broken down into 6 hour time windows. An example of some of the "whole forecast" gridded outputs, as displayed in the web reports, is shown in Figure 10. The nowcast ensembles are used to give updates in between the short-range blended ensemble based outputs. Nowcast-based outputs are produced for the whole forecast period only (T+3 to T+7 hours). Importantly, forecasters are able to view any FEWS Glasgow forecast from the past 36 hours enabling run-to-run variability to be assessed.

3.6 Scottish Flood Forecasting Service operational set-up and use of the Glasgow Pilot during the Commonwealth Games

For the Pilot Study, the model was run operationally throughout the summer of 2014 and used to support the national Flood Guidance Statement and flood alerts for the Glasgow area. For the period of the Commonwealth Games between 18 July and 4 August 2014, SEPA provided additional flood forecasting services through the Scottish Flood Forecasting Service directly in support of the Commonwealth Games. These services consisted of a bespoke Surface Water Flood Guidance Statement for Glasgow and an increased briefing and advisory service.

The Glasgow Daily Surface Water Flood Forecast (DSWFF) was issued every afternoon at 17:00 to responders based on the blended ensemble forecast from 13:00 GMT. An example Guidance Statement is shown in Figure 11. This contains expert interpretation of the FEWS Glasgow output and includes the following elements: a summary of surface water flood risk (based on the Flood Risk Matrix) for the next 24 hours, a weather summary, a detailed assessment of the surface water flood risk and information on the start and end-time of heightened risk. When relevant, a list of possible impacts was included. In addition to the Guidance Statement, expert trained recipients (such as SEPA's Flood Advisors and Met Office Meteorologists and Civil Contingency Advisors) were provided with summary displays of the raw model output. These were accompanied by a written Briefing Note that explained the key points in the forecast; commented on how the forecast should be interpreted; gave additional information on possible magnitude of impacts, uncertainty and timings; explained why there were differences to other products; gave some context to the forecast through comparison with previous events and stated when further updates would be available. An example Briefing Note is given in Figure 12. To accompany each Guidance Statement the SFFS also provided a verbal brief to the SEPA Resilience Officers working in the Multi Agency Control Centre during the Games.

The 17:00 issue time was selected to balance the availability of rainfall forecast data and the formal briefing schedule within the Games Multi Agency Control Centre. For future use, the Steering Group identified that if the restriction on scheduled meteorological forecast run times was lifted, a product issued earlier in the afternoon (~15:30) would be more beneficial to local councils. When required in increased risk situations an update could be produced at 08:00 with the potential to produce further updates throughout the day if needed. However, this was not required during the period of the Games. In practice, the written Briefing Note was updated more regularly than the formal Guidance Statement as this was found to provide sufficient reassurance and information for briefings for the type of events experienced during the operational period.

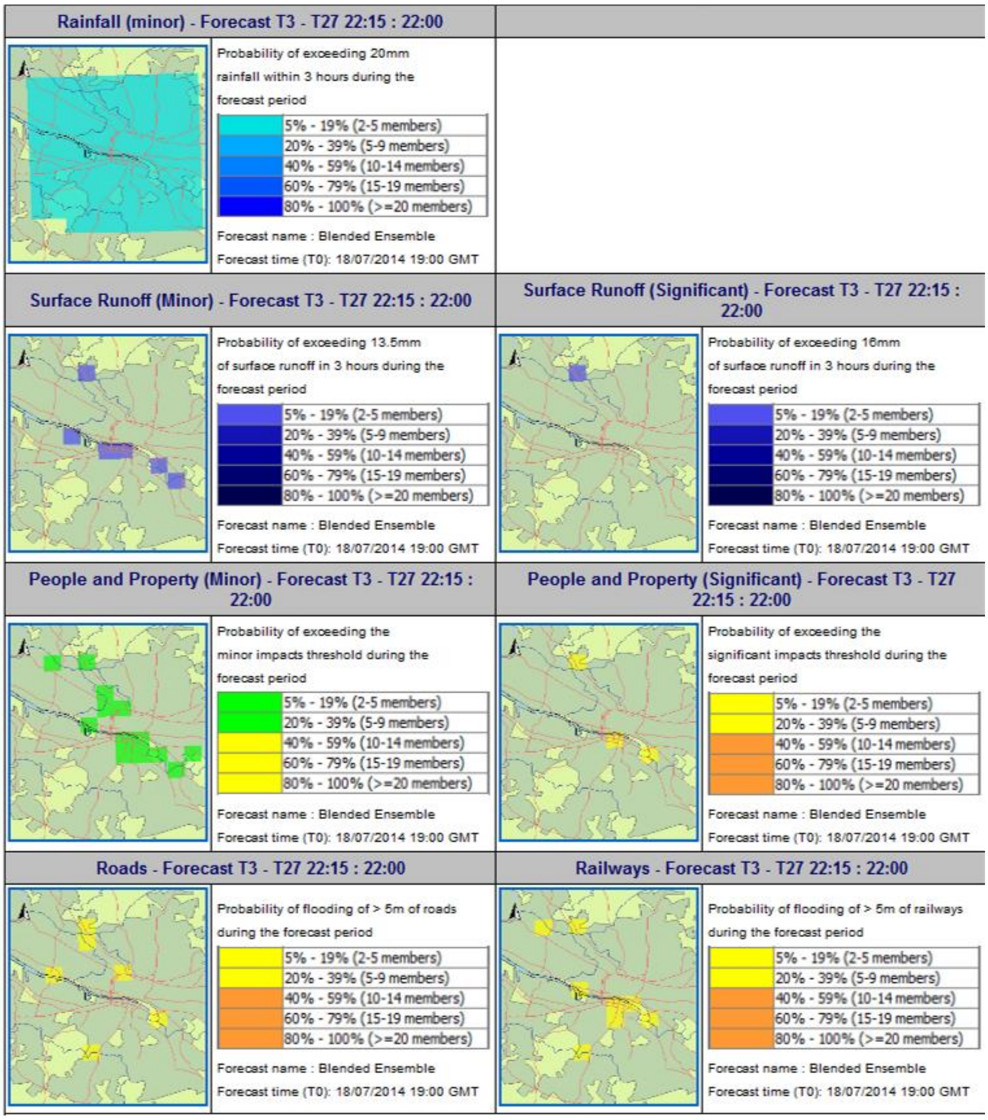


Figure 10 FEWS Glasgow 24 hour Summary using the blended ensemble forecast from 19:00 18 July 2014.

Scottish Flood Forecasting Service
Working in partnership

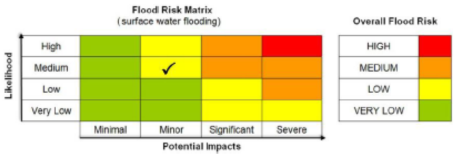
Glasgow Surface Water Flood Forecast
Issued at 17:00hrs Sunday 03 August 2014

Our assessment of surface water flood risk in Central Glasgow for the next 24 hours is below. This statement is valid at the time of issue.

Headline surface water flood risk

The overall surface water flood risk for Glasgow for Sunday evening is LOW. The flood risk on Monday is VERY LOW.

Minor disruption is possible including flooding and disruption to infrastructure and transport links. The risk is highest in the north and centre of Glasgow.



Weather Situation

Further rain this afternoon, evening and overnight, occasionally heavy but becoming patchier and unlikely to be as heavy as this afternoon. Rain gradually clearing north during Monday morning.

General overview of surface water flood risk in Glasgow

The surface water flood risk for Glasgow for Sunday evening is LOW and on Monday is VERY LOW.

Following heavy rain witnessed on Sunday afternoon and further lighter rain forecast throughout the evening, there is an increase in the flood risk to the north and centre of Glasgow, primarily to main transport routes in these areas.

Typical impacts will include standing water and spray on the road network. Transport links to and from event venues, especially the city centre, may be impacted. Rail links and infrastructure may also be at risk. Residual impacts may continue into Monday however these are expected to be very isolated and minor, if at all.

Potential flooding impacts may include:
Transport
- City centre roads
- M8 J14-18

Surface water flood risk heightened from: 15:00hrs 3rd August 2014
Expected time of highest risk: 17:00hrs 3rd August 2014
Expected end of heightened risk: 18:00hrs 3rd August 2014

General overview of other sources of flood risk in West Central Scotland (See the Scottish Flood Forecasting Service Flood Guidance Statement issued daily at 10:30hrs for details)

River Flood Risk: Very Low
Coastal Flood Risk: Very Low

No further Glasgow Surface Water Flood Forecast daily assessments are scheduled, unless the situation changes significantly.

Figure 11 Example of the Glasgow Daily Surface Water Flood Forecast issued at 17:00 3 August 2015.

This message was sent with High importance.

From: SFFS Operational
Sent: Fri 01/08/2014 17:10
To:
Cc:
Subject: Glasgow DSWFF 3 minute brief

This is the three minute brief from the SFFS Commonwealth Games Flood Forecasting Hydrologist on 01/08/2014 17:00

What? e.g. What is the briefing about? What is the current situation? What is known? What is the weather forecast?
1. The GDSWFF has the surface water flood risk for Glasgow for Saturday as VERY LOW.
2. A period of drier weather is expected on Friday evening then rain is forecast for Glasgow from Saturday afternoon and overnight.
3. There is the potential for periods of heavier rain within this broader wet period, particularly during the evening (typically 20- 30mm is possible during Saturday)
4. The national Flood Guidance Statement indicates a low flood risk for West Central Scotland however the main area of concern is over the higher ground rather than Glasgow itself
5. A SEPA flood alert has been issued for West Central Scotland again this is not directly due to concerns over Glasgow itself
6. A Met Office NSWWS warning is in place for heavy rain over a large part of the UK

Now what? e.g. What does this mean? How can the situation be interpreted? Comment on uncertainty. What should the key message to responders be?
1. At present, surface water flooding is not a major concern for Glasgow during the day on Saturday.
2. If we are unlucky enough to get one of the heavier showers, impacts should only be isolated and minor in nature, possibly causing flooding of roads in known problem spots
3. There is a high degree of uncertainty about the location and timing of the heaviest rainfall. This will be kept under review.
4. The heaviest rainfall in Glasgow is currently forecast for Saturday evening and overnight. This is outside the model range. More details will be available on Saturday morning.
5. For reference on 10th June 2014 (the event used in the FEWS Glasgow training session) the observed hourly rainfall rates were around 10-15mm per hour this caused localised, short lived, minor flooding of some roads in Glasgow. The forecast for tomorrow currently doesn't suggest heavier rain than this, although it cannot be ruled out in a worst case scenario.

So what? e.g. What can this lead to? What might the implications be for Glasgow and the Games? What do we need to do? When will update be available? Will any alerts be issued?
1. Generally no disruption from flooding is expected during the day on Saturday.
2. It is advisable to keep a close eye on forecasts in case of any change for the worse.
3. A morning update of the Daily Surface Water Flood Forecasting may be issued if models start to indicate impacts for Saturday evening and overnight.
4. Given the wider risk across southern Scotland transport to and from Glasgow may be affected (refer to the national Flood Guidance Statement and Flood alerts for details)

Duty Commonwealth Games Flood Forecasting Hydrologist

Figure 12 Example of the 3 minute Briefing Note issued in support of the Glasgow Daily Surface Water Flood Forecast on 1 August 2015.

During the operational period of the Games, 18 Glasgow DSWFFs were issued on 16 days with two additional updates. Of these, 9 days included concerns for minor surface water flood impacts although in most cases the likelihood of occurrence was very low (figure 13). Three case studies are discussed in Section 3.7.

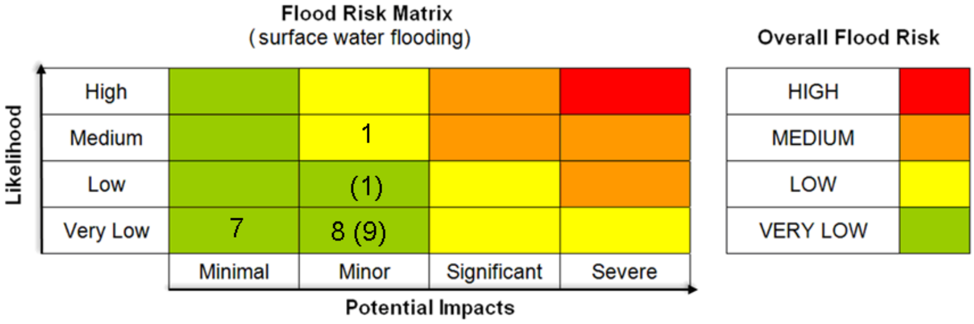


Figure 13 Summary of overall daily surface water flood risk assessment for Glasgow during the Games. Numbers in brackets include any sub-daily updates.

3.7 Model verification and testing

Verifying a probabilistic forecast system rigorously requires running the system over a long period of time and good quality observed data to test against. Although this was not possible for the Pilot Study due to its short duration and the challenges of collating comprehensive impact data, there was still much to gain from analysing specific case studies including borderline or non-events. This analysis benefited from a concerted effort during the Pilot Study to collate any relevant impact information from across the stakeholders, responders and anecdotally immediately after any event.

Whilst the weather during the Commonwealth Games was largely fine, there were occasions when the additional surface water guidance provided a real benefit to the organisers and responders. This took two forms, firstly enabling the SFFS to advise that, although heavy rainfall was forecast in the wider West Central Scotland region, flooding impacts in Glasgow itself were unlikely. Secondly, as was the case on the last weekend of the Games, providing information on the timing, likely impacts and possibility of flooding in Glasgow. The performance over the Pilot Study in terms of these two benefit scenarios demonstrates its suitability and value for use as a surface water alerting tool for urban areas. A brief summary of the performance of the tool during three different case study events follows.

3.7.1 Case study events

10 June 2014

This was the first event that the tool was tested in earnest and was a useful trial in advance of the Commonwealth Games. On 10 June minimal surface water flooding was reported by a member of SEPA staff in Glasgow causing difficult driving conditions and some transport disruption. FEWS Glasgow was operated in standalone-mode for this event and identified two ensemble members exceeding the low surface runoff threshold and some minor people and property and transport threshold exceedances. This reasonable agreement of the tool with the anecdotal impact reports gave confidence in using the model output during the Games itself.

18-19 July 2014

The 18-19 July provided a good example of a borderline event where more targeted forecasts for Glasgow could be provided. On Friday 18 July 2014 the potential for heavy and possibly thundery rain across southern Scotland was forecast for the following day. The national Flood Guidance Statement (FGS) communicated a low overall flood risk over many regions of Scotland, due to a very low likelihood of significant disruption from surface water flooding across a large area. Because the National FGS highlighted this risk for the region containing Glasgow, there was a challenge to maintain consistency and clear messaging between the national FGS and the Glasgow DSWFF. Also a regional flood alert was eventually issued during 19 July for surface water flooding.

FEWS Glasgow proved very useful to give the forecaster confidence that although thunderstorms were expected over a large area of the UK, the possibility of impacts in Glasgow itself remained very low. An example forecast output is given in Figure 10, showing there was a very low probability of exceeding the rainfall threshold, limited surface runoff was expected and any possible impacts were isolated and unlikely. This meant a more targeted story for Glasgow could be communicated within the backdrop of the wider area low risk (yellow) guidance from the national FGS. In practice the forecast thunderstorms did not materialise over Glasgow and no impacts were reported. Further details are provided in Speight et al. (2015).

2–3 August 2014

Persistent heavy rain was forecast across the final weekend of the Games, particularly for Sunday, with possible embedded heavier downpours. There was minor disruption to athletics events on Saturday evening and Sunday's cycle road race was very wet with competitors describing the conditions as "atrocious". There were isolated reports of flooding-related disruption across the city (Table 2) and temporary diversions at Glasgow Airport due to rain and wind. The Glasgow DSWFF was raised to low overall risk for the first time on the afternoon of Sunday 3 August.

Table 2 Reported flooding impacts during 2-3 August 2014, the final weekend of the Games.

Time of report	Impact	Reported by
2 August evening athletics	Large puddles and small amounts of flowing water near Hampden Park around 6:30pm. Some minor disruption to athletics.	Member of SEPA attending the Games
21:17 2 August	Giffnock flooding from drains/sewer and burn next to road. Not affecting property.	Member of the public to SEPA
21:41 2 August	Helensburgh drain overflow flooding shop	Member of the public to SEPA
14:39 3 August	Paisley flooding from small burn. Occurred last night and again today.	Member of the public to SEPA
15:13 3 August	Flooding on the M8 Junction 15	SEPA Resilience Officer
15:13 3 August	Drains lifting on the A82 cut-off from the M8	SEPA Resilience Officer
16:59 3 August	Large amount of surface water at the Baldinnie Road Park and Ride	SEPA Resilience Officer

SEPA's existing Heavy Rainfall Alert tool (SFFS, 2013) showed a high level of variability in the location of the heaviest rainfall for the Sunday afternoon. The Northwest Highlands were highlighted from the 09:00 forecast on the Saturday but by the morning of 3 August 2014 Glasgow was clearly identified as an area of concern with probabilities of around 70% for 20mm of rainfall in 3 hours. In reality there were two distinct rainfall events: one on the Saturday evening and one on Sunday afternoon.

The maximum surface runoff time-series plots for Saturday 2 August indicated some uncertainty about the timing and location of the heaviest rainfall with a wide spread of ensemble members and peaks distributed across the day. All forecasts had some members exceeding the 7-10mm runoff threshold at which impacts are forecast to start occurring. The 01:00 2 August blended ensemble forecast (Figure 14, left) identified the highest risk for the Saturday evening to the early hours of Sunday morning with four members crossing the 13.5mm surface runoff threshold. It was therefore not possible to be confident that any flooding impacts would occur and the Glasgow DSWFF stated a low likelihood of minor impacts.

In contrast, the surface runoff time-series plots for 3 August showed much higher consistency in the timing of the event peak but the probability of exceeding the impact thresholds remained low (so very low risk) until the forecasts near the start of the rainfall event (Figure 14, right). In most cases only a couple of extreme ensembles crossed the runoff thresholds but notably by the afternoon of 3 August the nowcast and blended ensembles (Figure 15) were indicating an increased probability of threshold exceedances. At this point the Glasgow DSWFF assessment was raised to a medium likelihood of minor impacts and the overall risk raised from very low to low for the first time.

Communicating the surface water flood risk messages during this event were challenging, particularly as the confidence and risk for Glasgow was evolving through the day. Again as the national Flood Guidance Statement considers larger geographical units, it had already identified a low risk (yellow) warning for medium confidence of minor impacts somewhere across the region encompassing Glasgow. The evolving surface water flood risk was effectively communicated to responders via SEPA's Resilience Office in the Multi Agency Control Centre via 3 minute updating Briefing Notes: an example is given in Figure 12. Further details of this case study are provided in Speight et al. (2015).

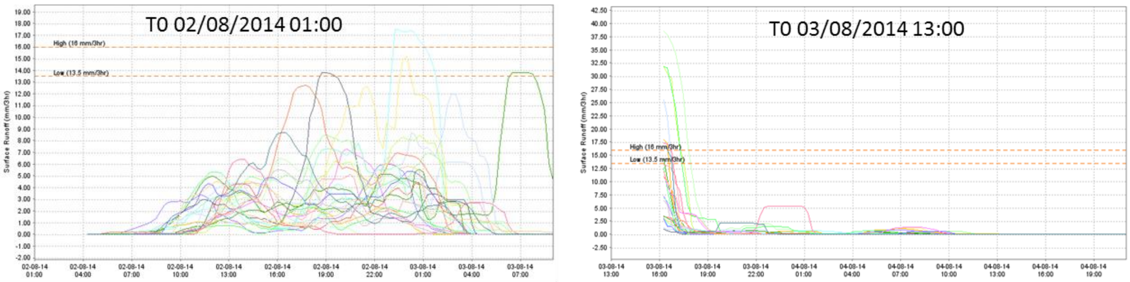


Figure 14 Surface runoff on Saturday 01:00 2 August (left) and Sunday 13:00 3 August (right).

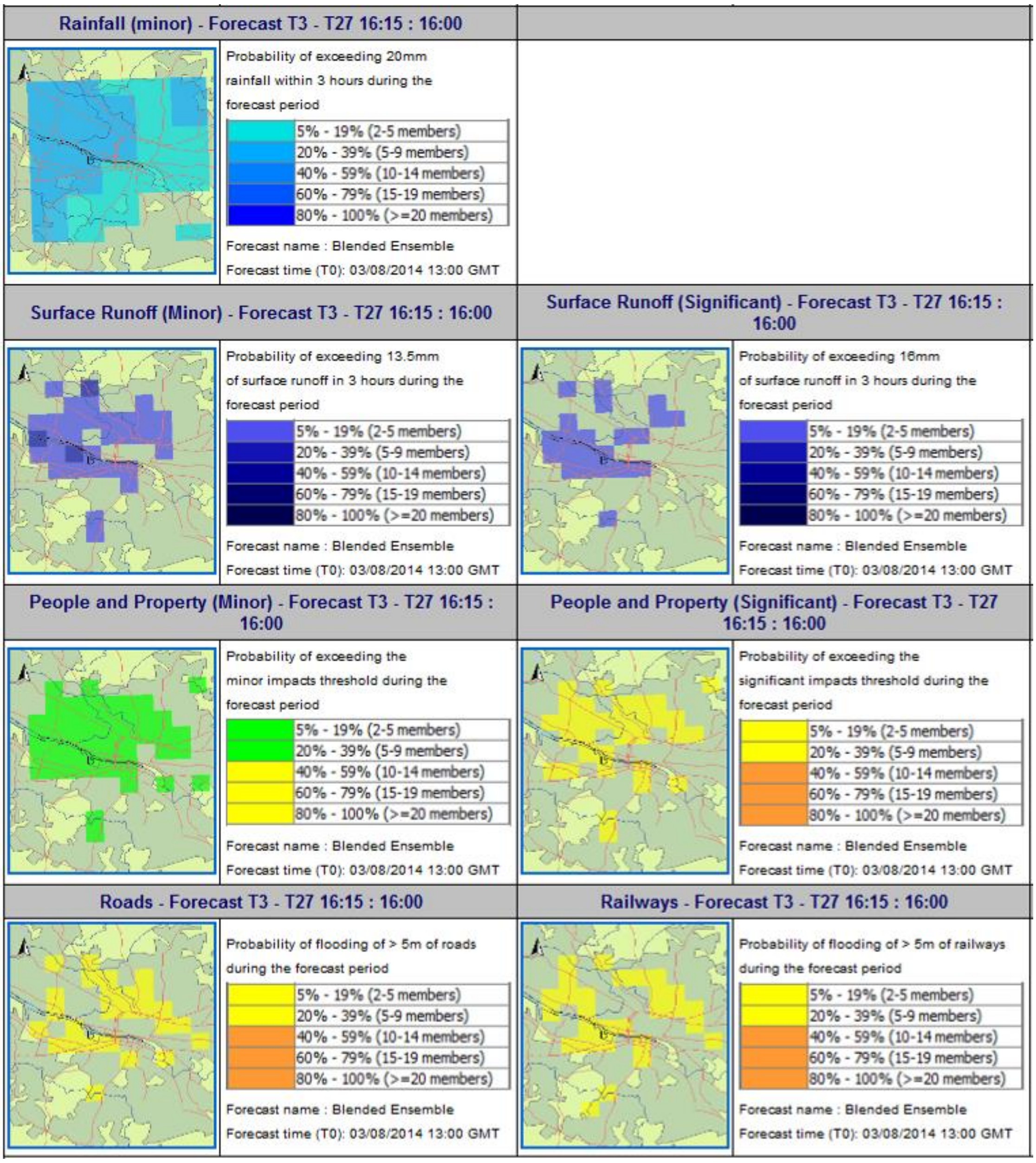


Figure 15 FEWS Glasgow 24 hour Summary using the blended ensemble forecast from 13:00 3 August 2014.

4.0 Transfer of Glasgow Pilot methodology to other parts of Scotland

The Pilot Study provided evidence that the surface water flood forecasting approach proposed has operational utility and wider roll-out of the approach to serve other urban communities in Scotland should be considered. This section considers what the next steps could be and is informed by some practical feedback from SEPA hydrologists that were involved in the Pilot Study.

4.1 **Practical feedback from SEPA hydrologists to consider prior to transfer to other areas**

- The maximum surface runoff accumulation thresholds used for the gridded outputs and surface runoff time-series plots should be revisited.
- The maximum surface runoff time-series plots were useful to gain insight into the ensemble members including identifying consistency between members.
- Using the full 32 hours of the blended ensemble should be considered. Currently only the maximum surface runoff time-series plots included the full 32 hours.
- FEWS Glasgow was used in conjunction with existing tools which is a sensible approach. Need to maintain clarity on which rainfall forecast data are used in which tool to aid interpretation.
- Essential to have access to FEWS Glasgow forecasts over the previous 36 hours to understand run-to-run consistency. Due to the 6 hour update of the blended ensemble, the inclusion of the nowcast ensembles proved a useful means of confirming if the forecast remained consistent with the previous blended ensemble forecast.
- Some cells consistently crossed the impact thresholds every time an event was forecast. Further offline work could perhaps be done to identify these locations prior to using the model in forecasting. However this serves to highlight the importance of the receptor locations even if the rainfall location is highly uncertain.
- The resources needed to deliver and communicate the Glasgow Daily Surface Water Flood Forecast were high. Contributing reasons for this were: the high profile of the Games, using a new tool, and the issuing times aligned to responder expectations (initially 17:00, and any updating required by 07:00). The level of resource and level of service expected needs to be balanced in any wider roll-out.

4.2 Transfer to other urban areas in Scotland

The methodology of the Pilot Study has been developed to use nationally available datasets so can theoretically, in the absence of any resource constraints, be easily transferred to another urban location in Scotland “as is”. However, it would seem logical to allow some scope for refining and developing the system further based on the experience gained during the Commonwealth Games pilot. There should also be the opportunity to reflect on whether a “city by city” parallel approach is the way to proceed or if a region-/area-wide approach should be followed that could, potentially, interface more readily with the existing regions used for the Flood Guidance Statement. To this end the recommendation for the next phase would be to refine and develop the system further using a small number of additional urban areas. Below are some refinement and development opportunities which will impact the possible technical and/or resource constraints.

4.2.1 Refinement and development opportunities

- **Reflect on "city by city" parallel approach or region-/area-wide approach.** This may include revisiting the current operational set-up of how FEWS Glasgow interfaces with FEWS Scotland.
- **Displaying outputs for multiple urban areas.** Some thought is required on the best way to present results from multiple urban areas. A simple approach is to have a "FEWS Glasgow" replica for each area but there may be better ways to give a high-level country-/region-wide summary?
- **Improve and refine current FEWS Glasgow displays.** Based on feedback from SEPA operational hydrologists, refinement of the current displays should be considered.
- **Inclusion of additional receptor information.** For the Pilot Study, certain details about the receptors could not be shared with the project. Their inclusion in the impact assessments could add significant value and so should be revisited.
- **Ensemble rainfall forecasts.** Potential to use and exploit existing and emerging ensemble rainfall forecast products. For example, more frequent use of the nowcasts (currently only 4 a day).
- **Automate city-/area-wide flood risk calculation.** Currently the methodology generates pixel-based risk assessments and the expert user provides the overall risk level for Glasgow. There is potential to develop automated methods to provide a "first guess" of the surface water flood risk for a region/area/city. This becomes more critical when considering applying the method to multiple urban areas and could impact on the efficiency of the system. There is potential to build on related work under the Natural Hazards Partnership.
- **Potential to use sub 1km scale application of G2G.** G2G can be applied at sub-1km scales which may improve the elements of the impact calculations (although aggregation to larger scales will still be required). This is also under investigation within the Natural Hazards Partnership.

4.2.2 Possible technical and/or resource constraints

The extent of the technical and/or resource constraints will, in part, be determined by the scope of the next phase of work.

- **SEPA computing infrastructure.** The FEWS Glasgow implementation on a 10 by 10 km impact area, embedded in a 22 by 22 km modelling area runs easily within 3 minutes. Increasing the coverage area and any increase in the forecasts (length, frequency, number of ensembles) would require additional computing resources.
- **SEPA's Regional Pluvial Flood Hazard (RPFH) maps and impact assessments.** Transfer to other urban areas requires these to be covered by the SEPA RPFH maps and associated impact assessments: this should be the case for urban areas of interest.
- **Ensemble rainfall forecasts.** Currently these were only received from the Met Office for the FEWS Glasgow domain and would need to be extended, or separate feeds set-up, for additional areas to be included.
- **Stakeholder engagement and managing expectations.** The success of the Glasgow Pilot Study was, in part, due to the close engagement with the appropriate stakeholders and end-users through activities like the Steering Group and training. This requires reasonable input from SEPA and commitment from end-users.

- **SEPA resource for service delivery.** The overheads in delivering the Glasgow Daily Surface Water Flood Forecast were high. The level of service that can be offered needs to be balanced by the available resource.
- **Multi-organisations.** The delivery of FEWS Glasgow involved multiple organisations. Whilst this worked successfully for the Pilot Study, it can also present challenges in aligning contributions.
- **Wider dissemination and communication**. The surface water alerting capability could be extended to members of the public. Methods of communicating surface water flooding risk need to be considered whilst taking account of existing services (Flood Guidance Statement, Flood Alerts, National Severe Weather Warning Service Alerts and Warnings).

5.0 Summary and Conclusion

The overall aim of the project was to review the current state-of-the-art in surface water flood forecasting for urban communities and to develop a potential methodology for real-time surface water flood forecasting in Scotland. This methodology was to be tested through a Pilot Study of a known flooding area in Glasgow's East End, operating in real-time to provide strategic flood guidance during the 2014 Commonwealth Games.

Two detailed review reports were produced and summarised by Ghimire et al. (2013b). The first report (Golding et al., 2013) reviewed recent advances in rainfall estimation and forecasting techniques and identified the best rainfall data for surface water flood forecasting. The second report (Ghimire et al., 2013a) reviewed the current surface water flood modelling techniques commonly used in the UK with a focus on their potential application for real-time forecasting in urban communities. Explicit high-resolution inundation models exist and are heavily used for surface water flooding design applications and in research activities. However, these are not yet ready for use in real-time ensemble forecasting of surface water inundation, especially within the time-scale of the Pilot Study. ISIS-FAST was identified as being potentially fast enough to run in real-time and a candidate for future consideration. High-resolution inundation modelling and delivery of services (e.g. cloud computing or High Performance Computing) is an area of active research and should continue to be monitored: real-time systems that meet SEPA's requirements could become feasible in the future.

The review concluded that the Grid-to-Grid (G2G) model should be used for surface water flood modelling in the subsequent operational phase of the project: involving application within the Glasgow Pilot for use during the Commonwealth Games. The domain of application was a 10 by 10 km grid encompassing the East End of Glasgow. Forecast rainfall inputs were to use both the ensemble STEPS nowcast system and the blended precipitation ensemble forecast, combining the 2km STEPS radar extrapolation forecast with the MOGREPS-UK 2.2km Numerical Weather Prediction model forecast.

A FEWS Glasgow application was created by Deltares which provided web-reports for the Pilot Study. Novel methodology allowed the impact of the G2G surface runoff ensemble forecasts to be assessed against different groups of receptors: People & Property, Transport, Road and Rail. Through equating the G2G surface runoff to the "effective rainfall" used by the JFlow+ inundation model that underpins SEPA's Regional Pluvial Flood Hazard (RPFH) maps and impact assessments, it was possible to derive surface runoff threshold grids which aligned to the minimal, minor, significant and severe impact thresholds used by the national Flood Guidance Statement (FGS). The ensemble forecasts then allowed the probability of exceeding the threshold (or likelihood) to be calculated and then the risk could be derived using the Flood Risk Matrix methodology of the FGS.

For the Pilot Study, the model set-up was run operationally throughout the summer of 2014 and used to support the national Flood Guidance Statement and flood alerts for the Glasgow area. For the period of the Commonwealth Games between 18 July and 4 August 2014, SEPA provided additional flood forecasting services through the Scottish Flood Forecasting Service directly in support of the Commonwealth Games. These services consisted of a bespoke Surface Water Flood Guidance Statement for Glasgow and an increased briefing and advisory service. Key outputs were the Glasgow Daily Surface Water Flood Forecast (DSWFF) which was issued every afternoon at 17:00, along with Briefing Notes which could be updated throughout the day.

The Glasgow Pilot represents a step-change in operational capability for the Scottish Flood Forecasting Service and is the UK's first surface water flood risk forecast with a lead-time of 24 hours. This successful pull-through of meteorological and hydrological science to operational benefit is particularly noteworthy in this challenging area.

Although rigorous assessment of the probabilistic tools provided requires a longer time period, case study analysis has proved extremely useful. For two events during the Commonwealth Games, FEWS Glasgow and the Daily Surface Water Flood Forecast were found to perform well within expectations. Positive feedback received from SEPA and the wider stakeholder and response community is further evidence of the success of the Glasgow Pilot and supports wider roll-out of the approach to serve other urban communities within Scotland. The recommendation for the next phase is to refine and develop the system further using a small number of additional urban areas. Potential development and refinement opportunities have been identified together with possible technical and/or resource constraints.

In conclusion, the research reported here has:

- Actively addressed the challenge of surface water flood forecasting
- Linked science and operational needs
- Provided a methodology for incorporating impacts of surface water flooding in real-time
- Learnt about the importance of communicating the risk of surface water flooding.

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