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Countrywide flood forecasting in Scotland: challenges for hydrometeorological model uncertainty and prediction

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Abstract The Scottish Flood Forecasting Service, a new partnership between the Met Office and the Scottish Environment Protection Agency, aims to make best use of weather and river forecasting expertise in providing improved flood resilience and vigilance for emergency responders across Scotland. Flood guidance employs a blend of experience, professional assessment and input from meteorological and hydrological models. For countrywide forecasts, the CEH-developed Grid-to-Grid model is planned to be the key forecasting tool: it employs rainfall estimates from raingauges, radar and weather models to produce forecast river flows up to 5 days ahead on a 1-km grid across the Scottish mainland. Probabilistic flood forecasts, using ensemble rainfalls as input, are planned in a future phase. Use of rainfall as input to hydrological models is a challenge in Scotland, especially given the terrain and sparse radar and raingauge network coverage, and makes forecasting uncertain. However, the merged hydrological and meteorological capabilities of the new service bring tangible benefits for improved flood forecasting.

Key words flood; forecasting; hydrometeorology

INTRODUCTION

The Flood Risk Management (Scotland) Act 2009 is the framework for managing flood risk in Scotland and gives the Scottish Environment Protection Agency (SEPA) strengthened and formalised duties for flood forecasting and warning. Under the Act, SEPA are committed to deliver a number of flood warning service developments: these include developing methods of working more closely with the Met Office, aiming to improve its technical capability to forecast, model and warn against all sources of flooding. A model for much closer working with the Met Office was developed through consultation with emergency responders, and based on international best practice such as the Flood Forecasting Centre (FFC) in England and Wales and the Service Central d'Hydrometeorologie et d'Appui a la Prevision des Inondations (SCHAPI) in France. The service aims include a combined flood forecasting service for Scotland, with fully integrated meteorological and hydrological aspects providing knowledge-transfer between the meteorological and hydrological services and the provision of regular, consistent information on flood threat to emergency responders (Cranston & Tavendale, 2012). As a result, the Scottish Flood Forecasting Service (SFFS) formally became operational on 8 March 2011.

Routinely, the service consists of collaboration between a SEPA Flood Forecasting Hydrologist generally based at SEPA's Perth office, working on a call-out basis; and the Met Office Public Weather Services desk, based at Met Office Aberdeen, which is a 24-h a day shift-working operation. Although working virtually, capability has been developed for SEPA and Met Office staff to work on their own separate corporate networks at the other organisation's location and co-locate as required. This will facilitate closer co-working during flood events and encourage interchange of knowledge and the build-up of shared expertise in weather and flood forecasting. On a daily basis there is routine dialogue, supported by model outputs, between the Flood Forecasting Hydrologist and the Duty Meteorologist to discuss the upcoming weather and potential flooding situation. The Flood Guidance Statement (FGS) is then compiled, with additional input from SEPA's Flood Warning Duty Officers to assess regional scale impact. The FGS displays information on flood risk from all sources, whether fluvial, tidal or surface water, using colour-coded maps to represent the next five days. The level of detail is greater for days 1 and 2. The flood risk for each area is calculated from an impact-likelihood matrix and is allocated a status of Very Low, Low, Medium or High. The FGS is distributed to emergency responders in Scotland with the aim of improving flood vigilance and resilience to potential flooding. The FGS complements the respective severe weather and flood warning services currently offered by the Met Office and SEPA.

This paper reviews the background to flood forecasting in Scotland, outlines the ongoing implementation of the G2G model for countrywide forecasting especially in relation to its use of rainfall data from radar and weather models, and future plans for probabilistic flood forecasting; the conclusion recognises the critical value of radar rainfall to the new flood forecasting service.

BACKGROUND TO FLOOD FORECASTING IN SCOTLAND

Real-time and forecast weather

The SFFS aims to bring together access to respective meteorological and hydrological forecasting data and tools. This includes sea- and land-based observations and data from rain, river and tide gauges. These are rapidly accessible and monitored via SEPA's Flood Early Warning System (FEWS) Scotland and the Met Office SWIFT system. High-resolution remotely-sensed data – including satellite; lightning detection and radar – contribute to monitoring and validating the rainfall pattern. These data are employed to initialise, calibrate and validate the dynamic weather prediction and hydrological forecast models and diagnostic tools used by the SFFS. Weather prediction models (both deterministic and probabilistic) and post-processing systems cover a variety of temporal and spatial resolutions from the next few hours to beyond 5 days. Deterministic weather model data and visualisation includes a "nowcast" from the UK Post Processing System (UKPP), UKV (1.5 km model to replace the UK 4 km) (Fig. 1), the North Atlantic and European model (NAE) and the Global Model (GM). These data as well as outputs in ensemble form are to be utilised in hydrological modelling, discussed further below.

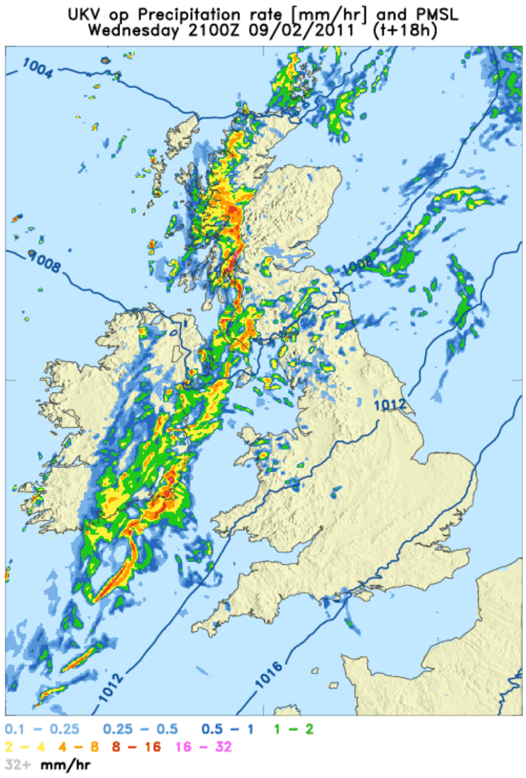

Fig. 1 Met Office UKV 1.5 km resolution forecast rainfall.

Hydrological forecasting

The drive for improved flood forecasting and warning in recent years fits with the move towards a more sustainable flood risk management approach (Tavendale, 2009). Flood warnings provide benefit to communities by allowing them the opportunity to take preventative action to mitigate flood impacts. To ensure confidence in the service, it is essential that sound science underpins the warnings: forecasts should aim to be timely and accurate whilst including an appreciation of their uncertainty. The drivers for an improved flood warning service have led to significant investment in flood forecasting capabilities in recent years. The introduction of major new flood warning schemes for the Strathclyde Region resulted in the development of the FEWS Scotland system – a national flood forecasting system bringing together hydrological and meteorological observations in a real-time environment (Cranston *et al.*, 2007). The best practice developed as part of this work has subsequently led to a rapid expansion of forecasting capabilities (Cranston & Tavendale, 2012).

HYDROLOGICAL MODEL AND FORECAST SYSTEM DEVELOPMENT

Flood forecasting systems have conventionally evolved in a targeted way with regard to cost–benefit appraisals of specific locations at risk, with deployment normally at a catchment, river basin or regional level: e.g. see Moore *et al.* (2009). The development of FEWS Scotland, along with related developments for England and Wales, provided the opportunity to develop integrated systems with consistency of forecasting software infrastructure at a national scale (Werner *et al.*, 2009). The model networks now configured reflect past and ongoing developments at catchment, area and regional scales and are targeted to make forecasts at specific locations.

It became apparent that a complementary, countrywide vision of flood risk in space and time was required. Research had progressed on distributed flood forecasting models for practical use, with particular focus on forecasting for ungauged areas and with the capability to forecast river flow "everywhere" over a continuous gridded domain (Moore *et al.*, 2006). A further impetus came from the Pitt Review of the summer 2007 floods, which recognised the need for a consistent countrywide early-alert of flood risk. The operational requirement and research activity combined to accelerate the development and assessment of CEH's Grid-to-Grid (G2G) model for countrywide operational deployment (Environment Agency, 2010; Cranston & Tavendale, 2012), together with improvements in its formulation (Moore *et al.*, 2007; Bell *et al.*, 2009).

The G2G model is a physical-conceptual distributed hydrological model that has runoff production and runoff routing components (Fig. 2). It is designed to make use of spatial datasets on terrain, soil, geology and land-cover properties. These underpin the spatial configuration of the model, leaving only a modest number of parameters to be calibrated against river flow observations across the country. Runoff production is controlled by a saturation excess mechanism in which the capacity of the soil to absorb water is controlled by soil properties and terrain slope through a probability-distributed formulation (Moore, 1985; Bell & Moore, 1998; Cole & Moore, 2009). Lateral transport of water through the soil, controlled by terrain slope and soil properties, can also be simulated. Routing of surface runoff through hillslope and channel pathways, under terrain control, employs kinematic wave approximations; similar representations are used to route subsurface flows in the groundwater component of the model. Interaction between water in the ground and the channel is allowed for through "return flow" functions.

In 2010, the Scottish Government approved funding to implement the G2G model across Scotland in support of the new flood forecasting service to enable river flow forecasts out to 5 days. Delivery of a configuration across Scotland was made in early March 2011 for testing purposes. A component of the system is HyradK (discussed later) which provides gridded rainfall estimates as input to the G2G from radar rainfall and/or raingauge sources. Operational implementation and evaluation was planned to start in June 2011, and model improvement and assessment using historical datasets is ongoing. Key ongoing developments will include the integration of a snowmelt component to the gridded model and production of probability-based forecasts.

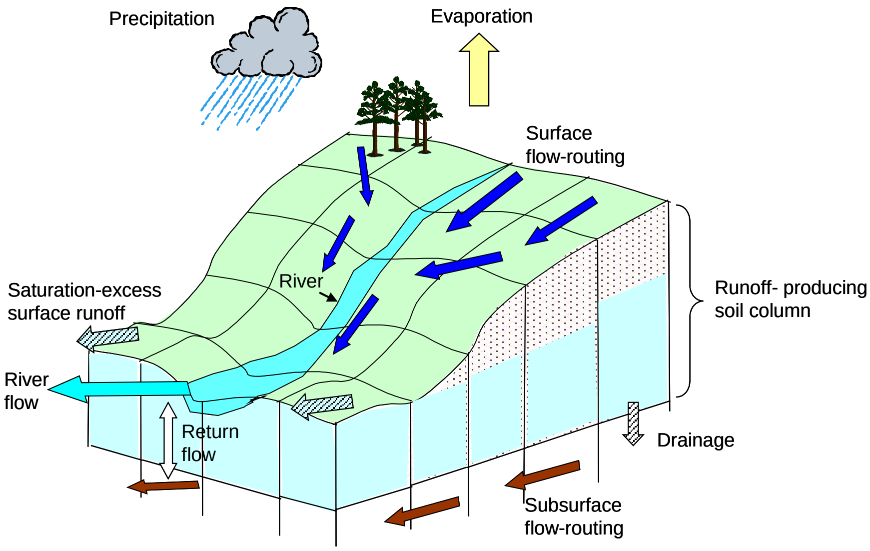

Fig. 2 Conceptual schematic of the G2G model.

Scotland's current flood forecasting system, FEWS Scotland, employs the Delft-FEWS operational flood forecasting platform (Werner *et al.*, 2004; Cranston *et al.*, 2007). This brings together meteorological (radar and forecast grids), hydrological (raingauges and river levels), reservoir (levels and outflows) and tidal (observed and astronomical) information. These data are imported, processed and displayed and are available to drive external hydrological and hydrodynamic river models whose outputs can be post-processed and evaluated.

To enable countrywide flood forecasting, both the HyradK and G2G models have been integrated as external modules into Delft-FEWS. HyradK brings together observed precipitation from SEPA's network of 185 raingauges and the Met Office composite radar product to produce an adjusted precipitation grid. The adjusted precipitation is then merged in Delft-FEWS with the forecasted NWP products to produce a continuous estimate of precipitation for input to the G2G model. River flow data from 214 gauges is also input to the G2G model to enable state-correction.

In a post-processing module, the G2G modelled river flows on a 1-km grid are compared with "flows of a given return period" grids for Scotland to give an estimate of the exceedence return period for each grid square. These are then transformed to give the warnings at gauge locations and maximum warning levels for larger flood alert areas. This enables the forecasting hydrologist to quickly identify where floods may occur for further verification and analysis.

UNCERTAINTY AND PREDICTION

Precipitation source hierarchy

The G2G model uses as input estimates of 15 min rainfall accumulations on a 1 km grid across Scotland. The observation sources available to make these estimates, up to the time the flood forecast is made, are: (i) rainfall values from a network of 182 tipping-bucket raingauges, and (ii) radar rain-rate values at 5 min intervals on a 1 km grid, derived as a composite primarily from the four radar installations in Scotland.

HyradK, the hydrological radar processing kernel of Hyrad developed by CEH, is used to form 15-min 1-km gridded rainfall accumulations of the three forms shown in Fig. 3. The left image shows the raingauge-only estimate, for an example time-frame, obtained by applying a multiquadric surface-fitting technique (Moore *et al.*, 2001, 2004; Cole & Moore, 2009) to the raingauge values alone (there are 25 gauges not reporting values, indicated in red). The right image shows the radar-only rainfall estimate formed using the 5 min rain-rates. A raingauge-adjusted radar estimate is shown in the central image, obtained by surface fitting to adjustment factors at each raingauge, formed as a modified ratio of gauge to coincident radar pixel rainfall values. Raingauge-adjusted estimates are seen in this example to be modified most in the central area of the image, where raingauges report larger values than indicated by the radar, but little change in the south where there is reasonable agreement.

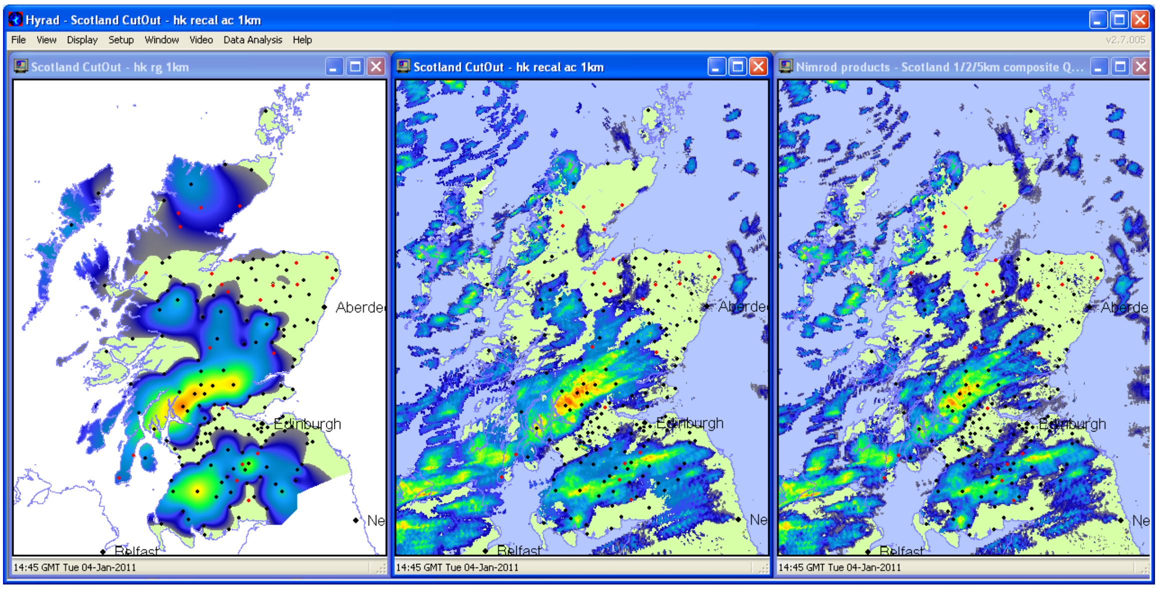

Fig. 3 HyradK 1 km gridded rainfall estimates over Scotland for 15 minute totals ending 14:45 h 4 January 2011. Left: raingauge-only; Middle: raingauge-adjusted radar; Right: radar-only. Raingauge locations indicated by black dots (red when missing observation).

A configurable hierarchy of gridded rainfall estimates is used within FEWS Scotland to decide on the rainfall input G2G will use. One possibility, in review as part of G2G calibration, is for the raingauge-adjusted radar estimate to have priority followed by radar-only, and then raingauge-only if radar data become unavailable. For future times, to obtain extended lead time forecasts out to 5 days, the system will use a 6 h 2 km deterministic "nowcast" (merging of advected radar data with short-period NWP) along with a 5-day NWP forecast based, as appropriate, on the UKV, NAE and Global atmospheric models. Provision is also being made to use 5-day temperature forecasts in the G2G snowmelt hydrology scheme which produces gridded estimates of snowmelt.

Weather radar and precipitation forecasting

Although the Central Lowlands of Scotland has high-resolution radar rainfall coverage, many parts suffer from poor (e.g. Highlands) or no coverage (Shetland Islands). However, the use of radar for flood forecasting in Scotland has demonstrable benefits (Cranston & Black, 2006), with raingauges unable to provide as effective spatial analysis of rainfall. Also, despite advances in numerical modelling, there remains uncertainty in the predictions of rainfall, especially at the resolutions and timescales associated with extremes storms of convective origin. Short-range rainfall forecasting tools such as STEPS (Bowler *et al.*, 2006), used as the basis of the deterministic nowcast, are heavily influenced in the first few hours by the quality of radar rainfall data. Poor coverage and radar anomalies can inevitably affect the skill of the rainfall forecasts and modelled river flows using them e.g. radar "anaprop" can lead to false alarms. However, with knowledge of these uncertainties the benefit of using rainfall predictions in flood forecasting is still greater than using none (Werner & Cranston, 2009). At larger synoptic scales and dealing with organised dynamic rainfall, tools like the Met Office's ensemble rainfall forecasts can be used to support probabilistic rainfall and flood forecasting. The "likelihood" of a flooding event occurring at a particular time and place can be predicted. Ensemble rainfall prediction in combination with G2G area-wide flood forecasting are seen as key tools helping address the operational challenge of dealing with uncertain forecasts.

CONCLUSION

The Scottish Flood Forecasting Service, although in relative infancy, is developing methods of close collaborative working so as to improve its capability to model, forecast and warn against all sources of flooding in Scotland. Uncertainties associated with both meteorological and hydrological forecasting techniques may be compounded when merged into a unified flood forecasting procedure for the whole of Scotland. However, methods such as HyradK and the precipitation source hierarchy presented here, alongside expert evaluation, aim to mitigate inaccuracies with radar rainfall, raingauge and weather model sources. Weather radar is a critical data source in this information chain leading to improved flood guidance. The forecasting service, by combining tools and expertise of meteorologists and hydrologists, issues a Flood Guidance Statement underpinned by a careful analysis of likelihood against impacts. This daily assessment of risk forms a valuable strategic and sustainable enhancement to flood management in Scotland.

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