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Real-time flood impacts mapping

Appendix 7: 10-day lead time numerical weather prediction products

SC120023/A7

Flood and Coastal Erosion Risk Management Research and Development Programme

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Professor Doug Wilson
Director, Research, Analysis and Evaluation

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1 Pro-forma summary

Ten-day lead time numerical weather prediction (NWP) products provide complementary information to current systems used by the Environment Agency by having an extended lead time and using different meteorological forcing.

Several flood indices and systems have been developed by the European Centre for Medium-Range Weather Forecasts (ECMWF):

- Extreme Run-off Index (ERI)
- European Flood Awareness System (EFAS)
- European Run-off Index based on Climatology (ERIC) – not used in this proof of concept (PoC)

Each of them has been designed for different types of flood events. ERI is an appropriate indicator to predict river floods for a wide range of conditions, including soil saturation and snowmelt-driven floods, yet it preserves capabilities in detecting floods driven by extreme precipitation over short durations. The hydrological model behind the EFAS system is designed to predict large-scale floods and, due to its continental scale set-up, is especially useful for transnational flood events. The ERIC index is the latest flash floods index within the EFAS system.

The Environment Agency is an EFAS partner and therefore has free access to the real-time forecasts from these systems. The forecasts from the ERIC index have been provided within the EFAS website since September 2015. The ERI is an independent ECMWF research forecasting product, but can also be accessed free of charge.

Operationally, forecasts based on probabilistic NWP are computationally expensive to implement. However, the aim of this PoC is to use NWP operationally run at the ECMWF and transfer the near real-time forecast outputs (for example, flood discharge, flood severity maps) to the servers of a third party (here the Environment Agency) for further analysis. As a result, the PoC involves post-processing and analysing forecast information. This can be fast and efficient, without the need for expensive hardware and long run times.

Further research is required to establish a robust link between simulated flood forecasts and flood impacts evaluated using conventional flood probabilities. This would allow users to operationally assess the impacts caused by potential floods with each new forecast, for a real-time assessment of risk, which could be used to inform planning and flood incident management activities.

2 Proof of concept overview

2.1 About this option

Name in Technical Options Report (Appendix 2): 10-day lead time NWP products

Number in Technical Options Report: Option 10

This option makes use of NWP ensemble products run at the ECMWF in collaboration with the European Commission's Joint Research Centre (JRC). The products provide probabilistic forecasts at up to 10-day lead times.

Alfieri et al. (2014) proposed a statistical method (the ERI) to derive 10-day river flow forecasts at European scale, utilising data from the 51-member ECMWF NWP model (Integrated Forecast System). Forecast lead times of 10 days were achieved, using 32km resolution outputs. The approach uses surface run-off forecasts from the land surface scheme of the ECMWF model, aggregated to basin scale and compared against a long-term (20 years) reference climatology of basin-wide run-off to estimate the rarity of a forecast event. It is an appropriate indicator to predict river floods for a wide range of conditions, including soil saturation and snowmelt-driven floods, yet it preserves capabilities in detecting floods driven by extreme precipitation over short durations.

The project team recommends the use of ERI forecasts in river basins with areas >1,000km^2, which is of the same magnitude as the grid resolution of the input data. The upper limit is less clear to define, as it is conditioned by:

- the increasing effect of the river routing with the basin size
- the timing of flood peaks in different tributaries of the same basin
- the dampening of the flood wave in its travel downstream and due to floodplains
- the interplay between surface, subsurface run-off and groundwater

In the current approach, the upper limit of basin size is of the order of 10^{5}km^2 and is bounded by a maximum accumulation period of surface run-off of 6 days. ERI is useful as a complementary ECMWF product, particularly for those river reaches where no hydrological parameter can be calibrated due to lack of observed discharge. Although this is a research ECMWF forecast product, it runs on a daily basis with 6-hourly outputs (Alfieri et al. 2014).

The success of the approach proposed in this PoC relies on the ERI methodology being capable of correctly predicting extreme flows in specific locations. As a result, this PoC was also tested alongside data from EFAS.[1] EFAS is a European Commission initiative to increase preparedness for riverine floods across Europe. It was triggered by the disastrous floods on the Elbe and Danube rivers in 2002 and seeks to increase preparedness for floods in Europe. The aim of EFAS is to gain time to put preparedness measures in place before major flood events strike, particularly for transnational river basins in the Member States as well as at European level. This is achieved by:

- providing complementary, added value information to national hydrological services

[1] www.efas.eu

- keeping the European Response and Co-ordination Centre informed about ongoing floods and the possibility of upcoming floods across Europe

The hydrological model used for EFAS is LISFLOOD. The model is a hybrid between a conceptual and a physical rainfall–run-off model combined with a routing module using kinematic wave in the river channel. LISFLOOD has been specifically designed for large river catchments. A particular feature of LISFLOOD is its strong use of an advanced geographical information system (GIS), in particular as a dynamic modelling framework.

EFAS provides up to 15-day river flood forecasts at the European scale utilising several meteorological data providers with a total amount of 65 ensemble members. Among them, EFAS uses the data from the 51-member ECMWF NWP Integrated Forecast System downscaled to a 5km × 5km grid, as for the ERI product. EFAS is an operational ECMWF forecast product, with 12-hourly outputs. Since November 2015, EFAS notifications have been sent out for a minimum upstream area of 2,000km^2 instead of the 4,000km^2 as previously.

EFAS has performed well in a number of flood events, such as the central Europe floods in June 2013 (EFAS 2013) and the Balkan floods in May 2014 (EFAS 2014a). A more recent example is the 2015 winter floods in the UK and Ireland. EFAS formal and informal flood and flash floods notifications generally performed well. All notifications issued gave at least one day advance notice in the respective basins (EFAS 2016).

In this PoC, modelled historical flows and/or exceeded return periods are compared with observed time series of flows or derived return periods respectively. As a result, rating or relationship curves are built between the modelled and observed products; these can be then used in real-time applications.

This method could **potentially** be used to provide a long-range ensemble-based assessment of risk across England and Wales, which could in turn be used for long-range, strategic planning activities (for example, mobilisation of flood protection measures to appropriate regions, rostering of duty staff, preparation of incident rooms, public awareness raising). Such an approach would be a 'long-range extension' to existing Grid-to-Grid (G2G) model forecasts, which currently provide ensemble forecasts out to 54 hours and a deterministic forecast out to 5 days ahead (Price et al. 2012).

These outputs could be further combined with pre-computed libraries of flood impacts to estimate the potential consequences. For example, a postcode level dataset of properties at risk could be pre-computed for given pre-defined flows or annual exceedance probabilities. This could be compiled from existing mapping with national coverage such as the Risk of Flooding from Rivers and Sea (RoFRS) and/or commercial flood mapping. Forecast flows could then be compared with this dataset to estimate flood impacts, with interpolation between the pre-computed impact assessments as necessary.

Alternatively, the approach could be coupled with a 2D inundation model (for example, the simplified fluvial modelling PoC tested in this study; see Appendix 5) or the pre-computed simulation library PoC (see Appendix 6). The final output from this process would therefore be a national scale long-range 'hotspot' map of likely flood impacts.

Note that the ECMWF products used within this PoC make reference to 'return period' and not to 'annual exceedance probability'. Therefore, for consistency with the data provider and the real-time forecast products, 'return period' is used here. However, there will be a need to agree on consistent terminology for flood probabilities if this PoC is implemented operationally.

2.2 Functional requirements

The Technical Options Report summarised the user requirements identified during the consultation exercise at the outset of this project. The user requirements were compiled into an evaluation matrix for this PoC, which is reproduced in Figure 2.1. The matrix was further refined after the consultation to capture the capabilities of the ECMWF products used here.

- Each row of the table presents the detail required by different user groups for a particular functional aspect. For example, spatial coverage may be local, regional or national scale.
- The user groups are shown as coloured bars along each row of the table. In this case, the user groups are Area Incident Rooms (green bars) and Gold/Silver Command (silver bars). A shaded bar implies that the particular user group requires the given functionality.
- If the PoC option meets a given acceptability criterion, it is assigned a ‘Y’.

FUNCTIONAL REQUIREMENTS

FLOOD SOURCE	Fluvial	Coastal	Surface Water	Groundwater	All sources
	Y				
FLOOD HAZARD	1D water levels	2D flood extents	2D flood depths / water levels	2D velocities and / or hazard rating	In-channel discharge or flood severity
		Y			Y
TEMPORAL INFORMATION	Onset of floodplain inundation	Time of maximum inundation	Duration of flooding	Dynamic representation of floodplain drying	
	Y	Y	Y		
SPATIAL COVERAGE	Local scale (e.g. town)	Regional scale (e.g. county)	National scale		
	Y	Y	Y		
SUITABILITY	Property	Parcels of land to street	Street to town	Town to county	County to national
				Y	Y
ASSET REPRESENTATION	Flood defences	Culverts and bridges	Other structures (e.g. gates, sluices, storage areas, pumping stations)		
ASSET PERFORMANCE	Breach inundation and overtopping: single asset failure	Breach inundation and overtopping: multiple asset failure	Within-event asset deterioration / failure	Worst case breach inundation	
TRANSPARENCY	Individual components can be interrogated / evaluated	Closed system, simplified model-wide confidence statements			
		Y			

Figure 2.1 Evaluation matrix: 10-day lead time NWP products

2.3 Workflow

The flow chart presented in Figure 2.2 shows, in generalised terms, how this option works. Subsequent sections of this appendix refer to the reference numbers in the flow chart to give:

- specific information about how the option was tested, and the data and software used in this project (Section 3)
- considerations for operational implementation (Section 5)

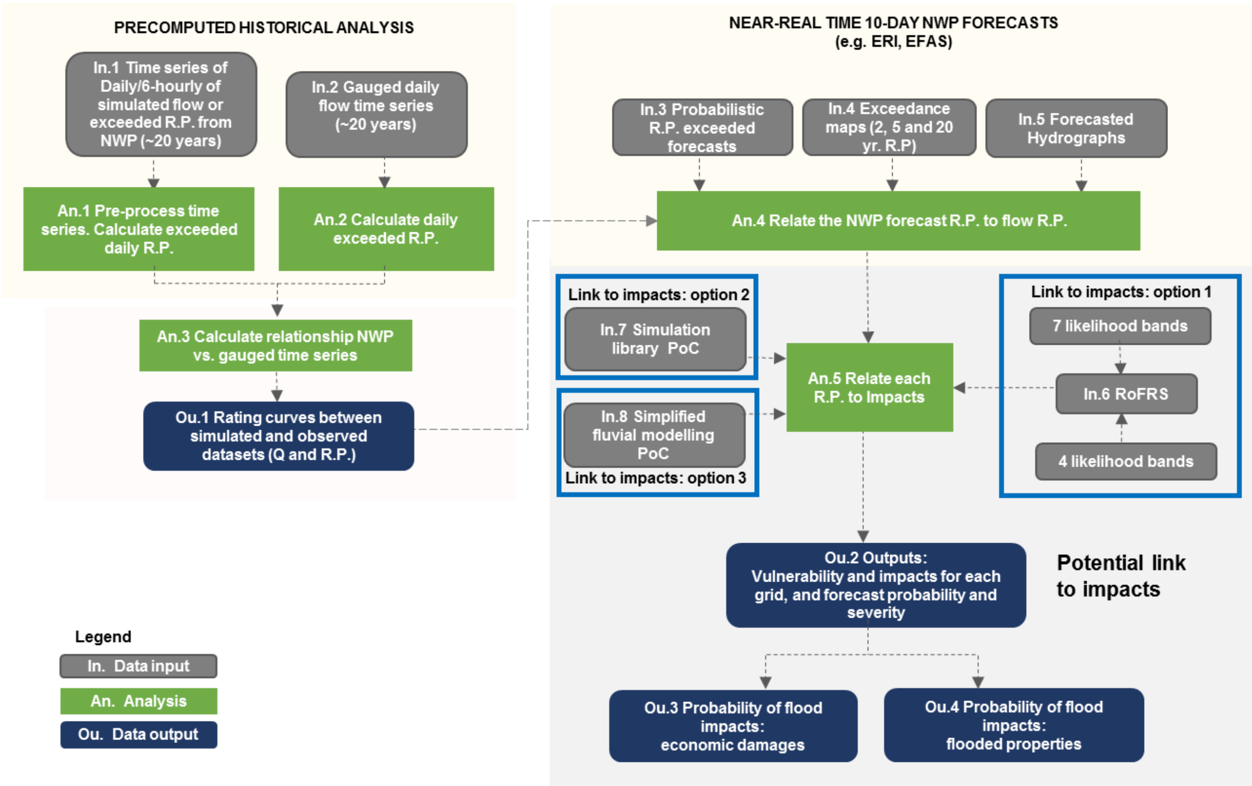

Figure 2.2 Flow chart showing PoC workflow for 10-day lead time NWP products

Notes: Q = river discharge; R.P. = return periods; Yr. = year

3 Proof of concept testing

3.1 Case studies

This section describes the case studies and data (evaluation data and model outputs; Table 3.1) available to this PoC option. Full descriptions of each case study and dataset are given in Section 5 of the main report.

Table 3.1 Summary of available case study data

	Morpeth	**Cockermouth**	**Thames**
Event	5–7 September 2008	12–30 November 2009 (peak flood 19–20 November 2009)	6–17 February 2014
Inputs	–	Hindcast and forecast of 10-day lead time probabilistic discharge and exceeded return periods	
Evaluation data	–	Observed river flows	
Evaluation tests[1]	A1, A2, B1, B2, C1	A1, A2, B1, B2, C1	A1, A2, B1, B2, C1
Outputs	–	10-day lead time of forecasts of simulated flood severity Relationship between simulation and observed river flows.	
Comments	ERI and EFAS were not operational at the time of this flood event.	EFAS has performed 2 sets of calibration rounds and model improvements since this flood event. EFAS has been fully operational since autumn 2012.	–

Notes: [1] See Section 4.1.5 of the main report for a description of each evaluation test. Tests shown in light grey were not available or were not considered by this option.

3.2 Testing the PoC option

Details of how the PoC option was implemented in this study, including filenames and versions, are given for reference in Tables 3.2 to 3.5. The flow chart for this option is shown in Figure 2.2.

3.2.1 Input data

Table 3.2 Input data (flow chart: In.1, In.1)

<table>
<tr><td>Model files and source</td><td>Cockermouth

ERI case study data: Cumbria2009_Gauges. For each forecast day (for example, 20091110_summary):

• Forecast hydrograph (for example, 1_RI2009111000.png)
• Forecast dataset (for example, 1_ RI2009111000.txt)
• Map of located/studied gauges: Gauge_Stations.map
• Layer with values for each exceeded return period: (Pr2.map; Pr5.map; Pr20.map)
• Upstream area: (UpsRepP_20091110.txt; UpsRepP.map)
• Summary (for example, SummaryRepP_2009111000.txt)

ERI long-term climatology: upSro_climatol_Cumbria.tss [6-hourly; start 5 January 1993 00:00, end 23 July 2012 00:00 (~20 years)]

EFAS case study data: not available – it was deleted from the ECMWF/JRC archive as the model underwent 2 further periods of calibration

EFAS hindcast: efas_hindcasts_Cumbria.xlsx (start 15 May 1995, end 8 March 2015 (~20 years); 1-day lead time, daily output, non-continuous time series (3–4 days’ gaps), 11 ensemble members];runs twice a week (Monday and Thursday)

Thames

ERI case study data: Thames2014_Gauges; for each forecast day (as above)

ERI long-term climatology: upSro_climatol_Thames.tss (as above)

EFAS case study data: Thames_2014_EFAS_51members. For forecast: (for example, efas_fcasts_Thames_2014012500)

EFAS hindcast: efas_hindcasts_Thames.xlsx (as above)</td></tr>
<tr><td>Required inputs</td><td>Location of ground river gauges – flow time series are the main validation dataset used to assess this option.

Where time series from gauging stations have been used, their National River Flow Archive (NFRA) ID is given in parentheses.

Cockermouth

(75001) St Johns Beck – Thirlmere U/S

(75002) River Derwent – Camerton

(75003) River Derwent – Ouse Bridge</td></tr>
</table>

	(75004) River Cocker – Southwaite Bridge (75005) River Derwent – Portinscale (75007) Glenderamackin – Threlkeld (75009) River Greta – Low Briery **Thames** (39001) Thames – Kingston (39121) Thames – Walton (39111) Thames – Staines (39072) Thames – Windsor (2604FQ; Wiski ID) Thames – Maidenhead (39130) Thames – Reading (39023) Wye – Bourne End Hedsor
File formats	NWP outputs formats (.map, .csv, .tss, .xlsx and .png) Flow–time series used to compare with simulated datasets (.csv)
Data overheads	Input time series files are of relatively very small size, but when considering the all-forecast outputs over time, there may be considerable increases in data volumes. For example, each ERI forecast day for the River Thames is ~2.74–7.6MB (for the 16 days tested in this case study). Although this is a relatively small size compared with the outputs from other PoCs, it is dependent on the number of locations of interest, model domain size and length of the time series. Data overheads may still need to be considered.

3.2.2 Intermediate processing

Table 3.3 Intermediate processing (flow chart: An.1, pre-process time series)

Software	
R 3.1.3 and R Studio 0.99.489: a free programming language and software environment for statistical computing and graphics (www.r-project.org) ArcGIS 10.2 (licence required) for mapping analysis (or other open source GIS software)	
Hardware	
Description	Several R scripts were developed and run to pre-process the time series and to obtain the format and values needed. ERI Analysis: '1_ERI_Climatology_processing.R' calculated the daily maximum ERI exceeded return period out of the 6-hourly data. EFAS Analysis: '1_Fill_mising_dates' fill NAs on the missing days in order to obtain a continuous time series;

	'2_Calculate_medians' calculates the median daily forecasted value out of the 51 ensemble members. Runs were undertaken on a PC with a 3.60GHz CPU and 16GB of RAM. However, the analysis does not require the full computing resource.
Size of model files (excluding outputs)	ERI analysis: Cockermouth: 2,594KB; Thames: 2,594KB EFAS analysis: Cockermouth:1,327 KB; Thames: 1,079KB/1,260KB
Network logistics	Intermediate run files were stored on the network folder.
Run times	Cockermouth: <1 minute Thames: <1 minute
Size of model domain	Cockermouth: study carried out at the gauged locations/grids Thames: study carried out at the gauged locations/grids

Table 3.4 Calculating daily exceeded return periods for river flow (flow chart: An.2)

Software	
Open source Python	
Hardware	
Description	A Python script was developed ('get_rp_from_flow.py') and run to calculate the exceeded return periods of the daily river flows. The methodology applied here is based on the H21 Evidence Update for National Risk Assessment 2016 project undertaken by JBA Consulting for the Environment Agency. A look-up approach, based on the Flood Estimation Handbook catchment descriptors, was used to establish a relationship between river flow measurements at selected (gauged) locations and the equivalent exceeded return periods. Where a location is not available on the pre-computed look-up table, the nearest (linear) interpolation point is used to extract the look-up flow–return period relationship. Runs were undertaken on a PC with a 3.60GHz CPU and 16GB of RAM. However, the analysis does not require the full computing resource.
Size of model files (excluding outputs)	Gauge analysis: Cockermouth: 372KB; Thames: 344KB
Network logistics	Intermediate run files were stored on the local drive, then transferred to a network drive.
Run times	Cockermouth: <1 minute; Thames: <1 minute
Size of model domain	Cockermouth: study carried out at the gauged locations/grid cells only Thames: study carried out at the gauged locations/grid cells only

Table 3.5 Calculating relationship NWP versus gauged time series (flow chart: An.3)

Software	
Open source R/R studio software. R Studio version: 0.99.489	
Hardware	
Description	Several R scripts were developed and run to obtain the relationship curves and graphs, between simulated and observed datasets. 2_ERI_NFRA_plots_Thames // 2_ERI_NFRA_plots_Cumbria 3_ERI_NFRA_RETURN_PERIODS_plots_Thames // 3_ERI_NFRA_RETURN_PERIODS_plots_Cumbria Runs were undertaken on a PC with a 3.60GHz CPU and 16GB of RAM. However, the analysis does not require the full computing resource.
Size of model files (excluding outputs)	ERI analysis: Cockermouth: 550KB; Thames: 544KB EFAS analysis: Cockermouth: 3,801KB; Thames: 3,258KB Gauges: Cockermouth: 371 + 465KB; Thames: 340 + 424KB
Network logistics	Intermediate run files were stored in a networked folder.
Run times	Cockermouth: <1 minute Thames: <1 minute
Size of model domain	Cockermouth: study carried out at the gauged locations/grid cells only Thames: study carried out at the gauged locations/grid cells only

3.2.3 Output data

Table 3.6 Flow chart: Ou.1 regression models between simulated and observed datasets (Q and return periods)

Outputs provided	Regression model relationship and associated plots (where possible) between NWP and river flows time series. This relationship can be based on flow–flow relationship or on exceeded return period between both datasets.
File sizes	ERI analysis: Cockermouth: 938KB; Thames: 940KB EFAS analysis: Cockermouth: 7.97MB; Thames: 7.36MB

3.2.4 Near real-time 10-day NWP forecast post-processing

Flow chart: In.3/4/5, An.5

In this PoC option, the flood impacts were assessed using a different methodology to the other PoC options described in Section 4 of the main report. The outcomes of these evaluation tests are presented in Section 4 of this appendix.

4 Proof of concept evaluation

This section provides detailed information on the outputs of the PoC. Its purpose is to provide supporting information for each case study event to demonstrate:

- the outputs available from the option
- the technical feasibility of the option
- the simulation performance of the option against observed data

The findings are summarised in Table 4.1.

Table 4.1 Summary of PoC findings

Case study	Findings
Cockermouth	Historical analysis (~20 years) of the return periods exceeded by the ERI during that period of study and by the gauged river flows did not provide a clear relationship between both datasets. However, when using the hindcast information from EFAS, the relationship is more evident, especially in terms of flows but less so in terms of exceeded severity thresholds. The ERI real-time forecasts provide up to 10-day lead time information on the extreme run-off as a proxy for a flood peak. In Cumbria, however, floods are often flashy, particularly when short duration, high intensity storms occur over steep, rapidly responding catchments. As a result, these types of floods are more challenging to fully capture many days in advance. For this case study, ERI provided useful forecasts 1–2 days before the flood onset. However, the study locations have an upstream area value smaller (25–400km^2) than the recommended to use for ERI (>1,000km^2). Therefore, the full potential performance from ERI might have not been achieved in this area (for example, longer lead time prior to the onset of the flood) In 2009, EFAS was still in pre-operational and testing mode. Forecasts for this case study were no longer available from the data providers (ECMWF/JRC). In October 2012, EFAS became operational and additional information such as bi-monthly bulletins with summaries on the flood and flash floods performance updated; further information has been available to stakeholders since then.
Thames	Historical analysis (~20 years) of the return period exceeded by the ERI and by the gauged flows did not provide a clear relationship between the datasets. However, when using the hindcast information from EFAS, the relationship is more evident, especially in terms of flows but less so in terms of exceeded severity thresholds. EFAS performed better for the Thames than with the rivers in Cumbria due to the river characteristics, shallower floodplain topography and longer duration of floods. The ERI real-time forecasts provide up to 10-day lead time information on the flood peak. In this case study, ERI provided useful and complementary information on the flood onset, duration and severity. As expected, it performed better on the River Thames due to the larger size of the catchment. Furthermore, the gauges located on the main River

Case study	Findings
	Thames exceeded the recommended minimum upstream area value (>1,000km^2) to use the ERI forecasts. For this period (7–17 February 2014) and river reach, no specific EFAS floods or flash flood alerts were sent out to EFAS partners (EFAS 2014b) because the forecasts were not very persistent. However, on the same river, 5 flood alerts were send during the December 2013 to January 2014 period (EFAS 2014c). The procedure is that EFAS alerts are sent direct to the Flood Forecasting Centre (EEC) and, along with the EFAS website information, are used to compile a 'Hydrological Assessment'.

4.1 Case study 1: Cockermouth, November 2009

4.1.1 Location

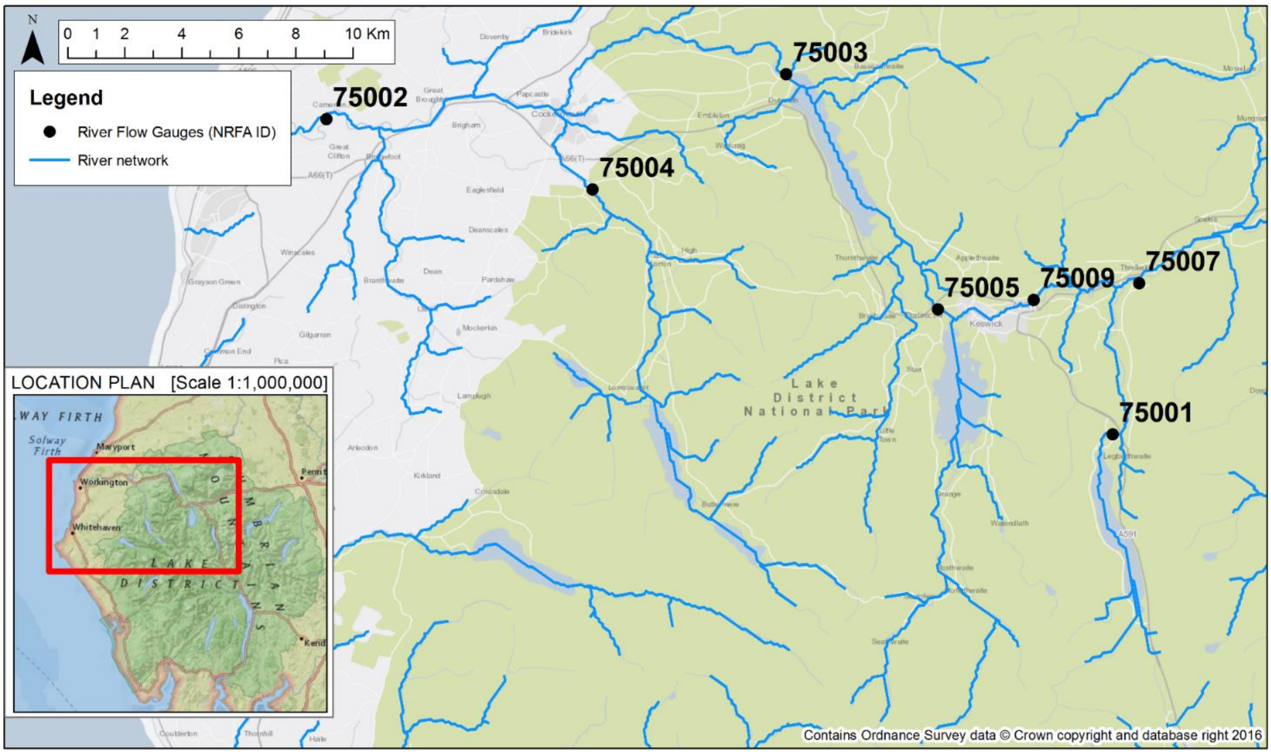

Figure 4.1 Location map for Cockermouth case study

4.1.2 Relationship between NWP products and river flow (An.3)

This section presents the results of the analysis (An.3) based on the relationship between the NWP historical/hindcast time series – ERI and EFAS – and river flows. For illustrative proposes, the results from only one of the locations are shown (Gauge 75003 – River Derwent at Ouse Bridge).

The River Derwent is the main source of flood risk to Cockermouth in this event, with predictions at Ouse Bridge, the main gauge upstream of the town, being particularly relevant. Results are available for all the locations shown in Figure 4.1, but are not reported here.

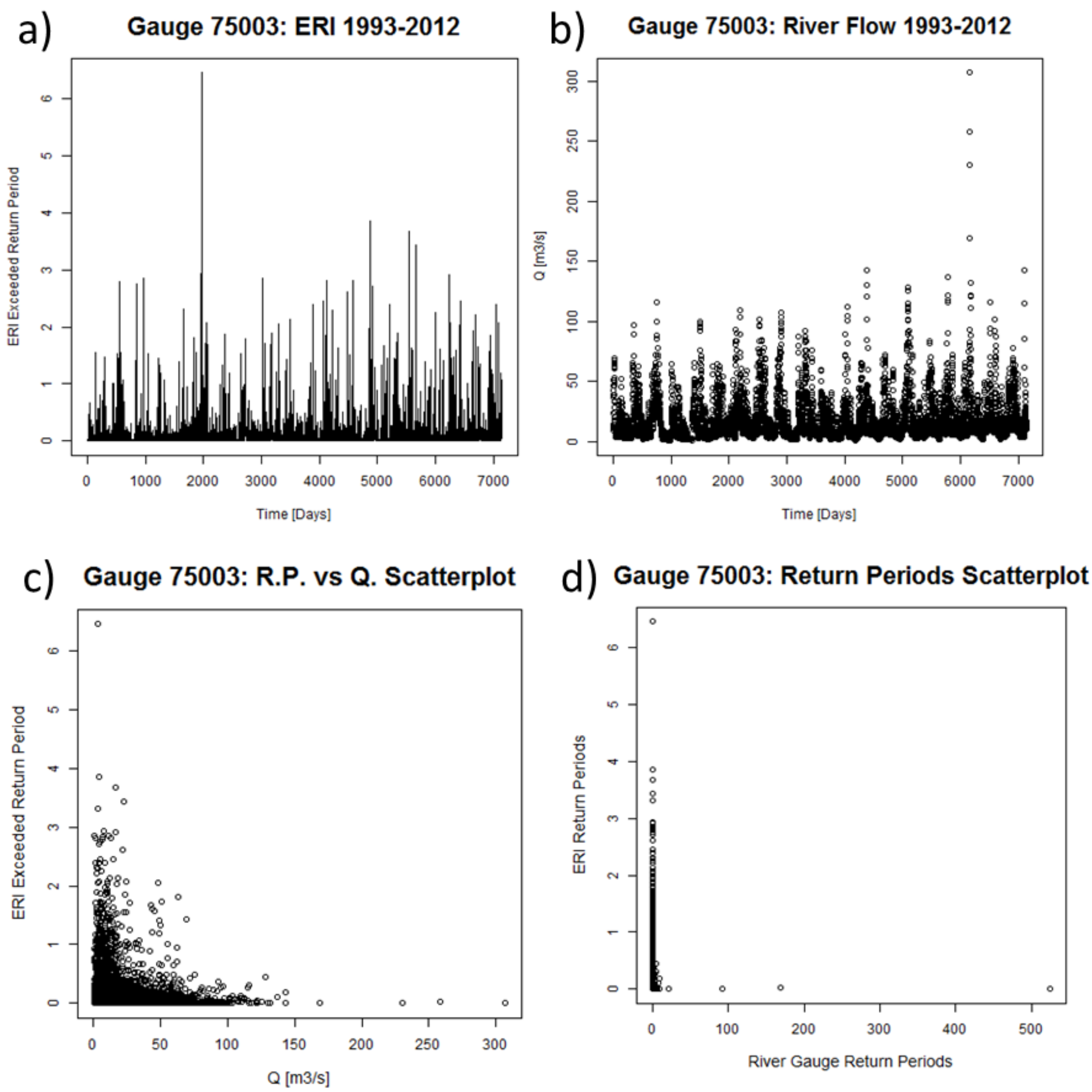

Figure 4.2 Comparison of modelled ERI return periods and observed river flow for gauge 75003 (River Derwent – Ouse Bridge)

Notes: The comparison was for the period available in both datasets (start 5 January 1993 00:00, end 23 July 2012 00:00).

Interpretation

Figure 4.2a displays time series from the ERI long-term climatology. It is an indication of extreme run-off values – larger values on the y-axis correspond to exceedence of higher ERI return periods. Figure 4.2b shows time series of river flow for the same period of time. Figure 4.2c correlates the 2 datasets. Finally, observed river flow time series were transformed into exceeded return periods, and the comparison with the ERI exceeded return periods is plotted in Figure 4.2d.

Overall, there is a very poor correlation between exceeded return periods based on ERI and return periods based on observed river flows (and also flow itself). It was therefore decided not to calculate further regression models, as they would have limited meaning. Similar outputs were found at all other studied gauge locations.

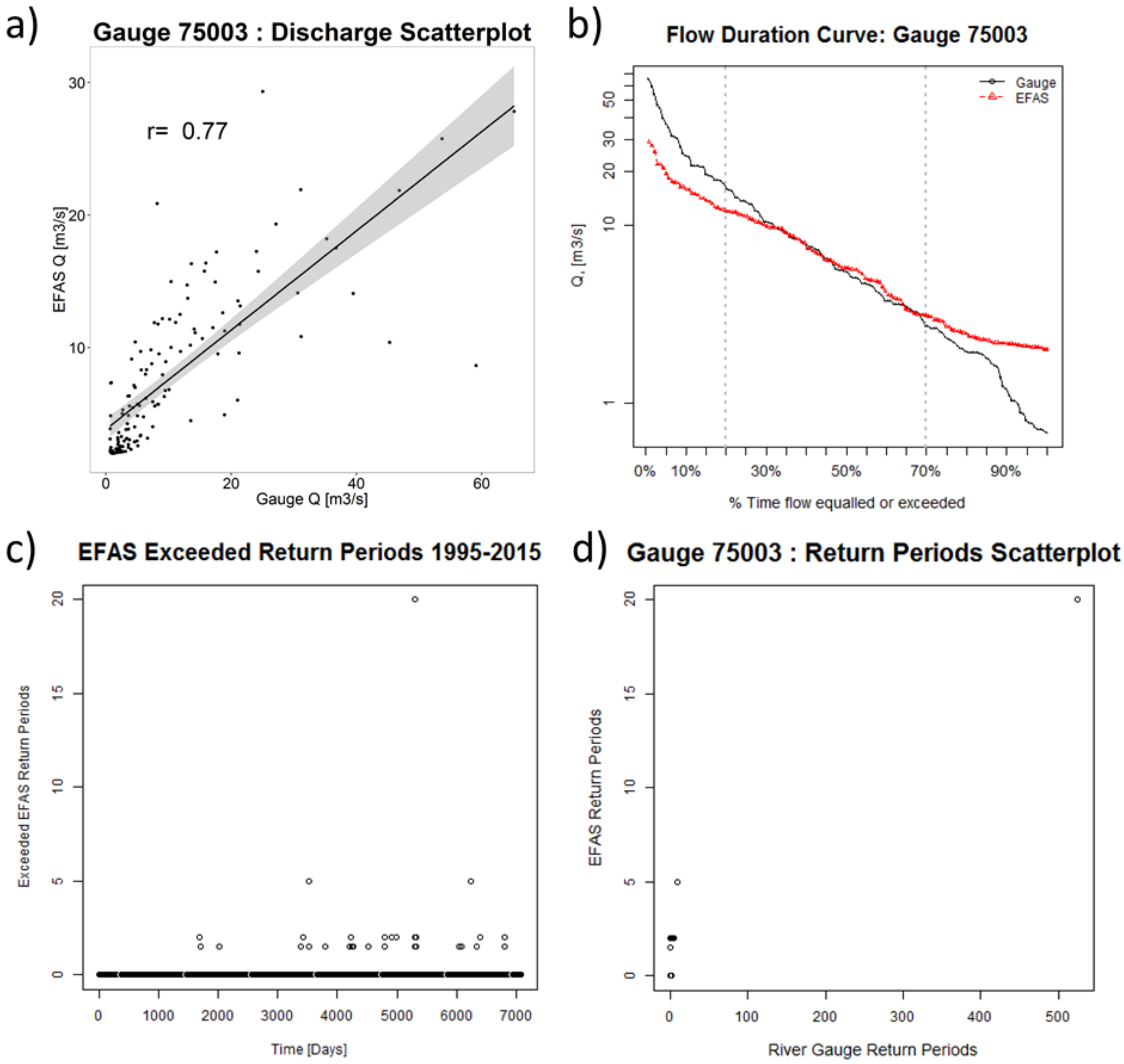

Figure 4.3 Comparison of modelled EFAS return periods and observed river flow for gauge 75003 (River Derwent – Ouse Bridge)

Notes: The comparison was made for the common available period (start 15 May 1995 00:00, end 8 March 2015 00:00).

Interpretation

Figure 4.3a correlates EFAS hindcast discharge time series and river flow time series. Compared with the scatterplot shown using the ERI return periods (Figure 4.2d), EFAS reproduces river flow at this location better. This is also shown by the flow duration curves of Figure 4.3b, based on EFAS and observed flows.

EFAS discharge values were transformed into exceeded return periods based on pre-computed values of threshold exceedances (1.5, 2, 5 and 20 year return periods) as shown in Figure 4.3c. Unlike river flows, EFAS values are only reported when they exceed specific thresholds, and therefore do not provide a continous time series. Figure 4.3d correlates the available EFAS and river gauge time series where return periods are exceeded.

Overall, the model performs satisfactorily for Cumbria, especially at locations further downstream in the catchment and on larger rivers; this is as expected due to the model grid resolution applied in EFAS. The 5-year return period was only exceeded on 3 occasions by EFAS during the 20 years of data available to the study at this location. This can also been seen at other locations in Cumbria.

As a result, the regression models obtained from the comparison between EFAS and river flow return periods contain few values to derive a relationship between datasets with a high level of confidence. In the future, a stronger relationship between the datasets could be estblished using a larger number of flood events, captured through a longer time series of EFAS hindcasts.

Note that the outlier present on the graphs above and for the other gauges (for example, gauges 75002, 75003, and 7005) relates to the values exceeded on the 20 November 2009 forecast, where the peak flow was registered.

4.1.3 Near real-time 10-day NWP forecast (An.4)

ERI near real-time forecast

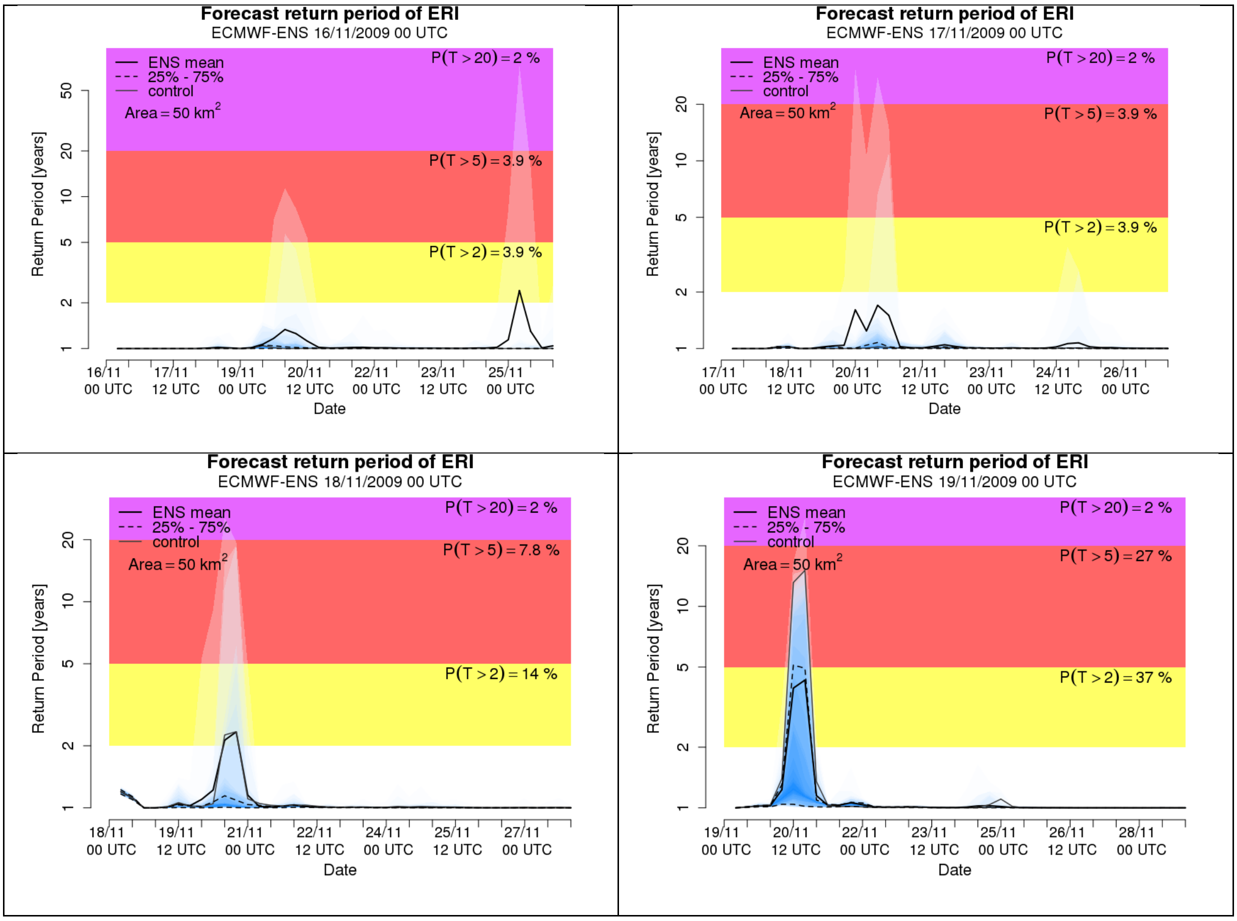

Figure 4.4 ERI forecast evolution on 16, 17, 18 and 19 November 2009 00 UTC at gauge 75003 (River Derwent – Ouse Bridge)

Notes: UTC = Universal Time Coordinated

Interpretation

ERI forecast provides probabilistic information (51 ensemble members) of extreme run-off up to 10 days in advance. As for EFAS, the ERI shows 3 fixed thresholds, based on simulated 2, 5 and 20-year return period events.

Using extreme run-off as a proxy for flood peak, the 16 November 2009 forecast for this location (gauge 75003) shows a very low probability that any of the fixed thresholds would be exceeded over the forecast horizon tested. Forecasts for 17 November show a similar situation. However, the probability of extreme run-off (that is, number of ensemble members above the threshold) occurring on 20 November at this location increased considerably in the forecasts made in the 2 days prior to the event (18 and 19 November).

From this analysis, it can be concluded that ERI forecasts are valuable as a probabilistic extreme run-off index with a 10-day forecast window. However, in terms of absolute return period values, it was not possible to accurately capture the full magnitude of the Cumbria 2009 flood as shown by ground observations.

Since September 2015, a new flash flood index, ERIC, has been operational within EFAS. Further information is provided in Section 6.

EFAS near real-time forecast

In 2009, EFAS was still in pre-operational and testing mode. Forecasts for this case study were no longer available from the data providers (ECMWF/JRC). In October 2012, EFAS became operational and stakeholders have been provided with additional information since that time, such as bi-monthly bulletins with summaries on the flood and flash floods performance, updates and other information.

4.1.4 Relationship between NWP forecast and potential flood impacts

The proposed methodology is explained in Section 4.2.4.

4.2 Case study 2: Thames, February 2014

4.2.1 Location

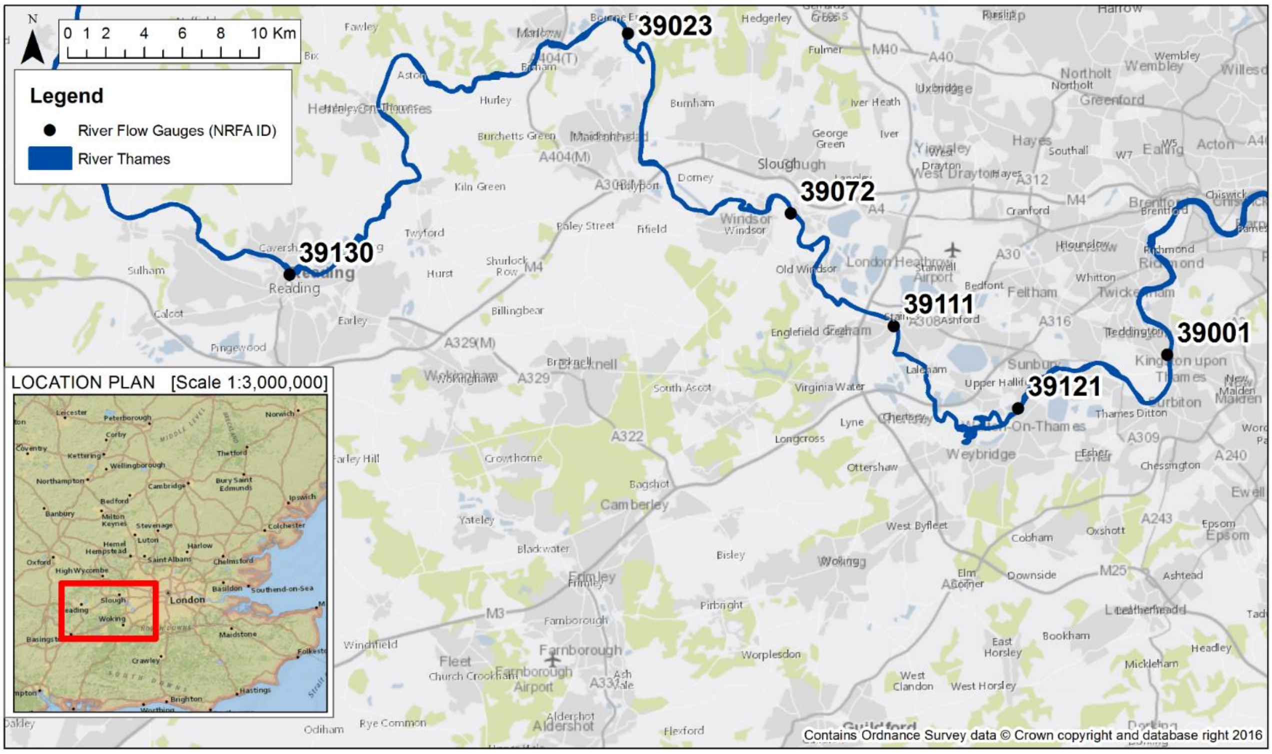

Figure 4.5 Location map for Thames case study

4.2.2 Relationship between NWP and river flow (An.3)

The results of the analysis are illustrated through one of the locations (Gauge 39121 – River Thames at Walton). This is towards the downstream extent of the reaches considered by this study and is representative of the catchment to that point. Results are available for all the locations shown in Figure 4.5, but are not reported here.

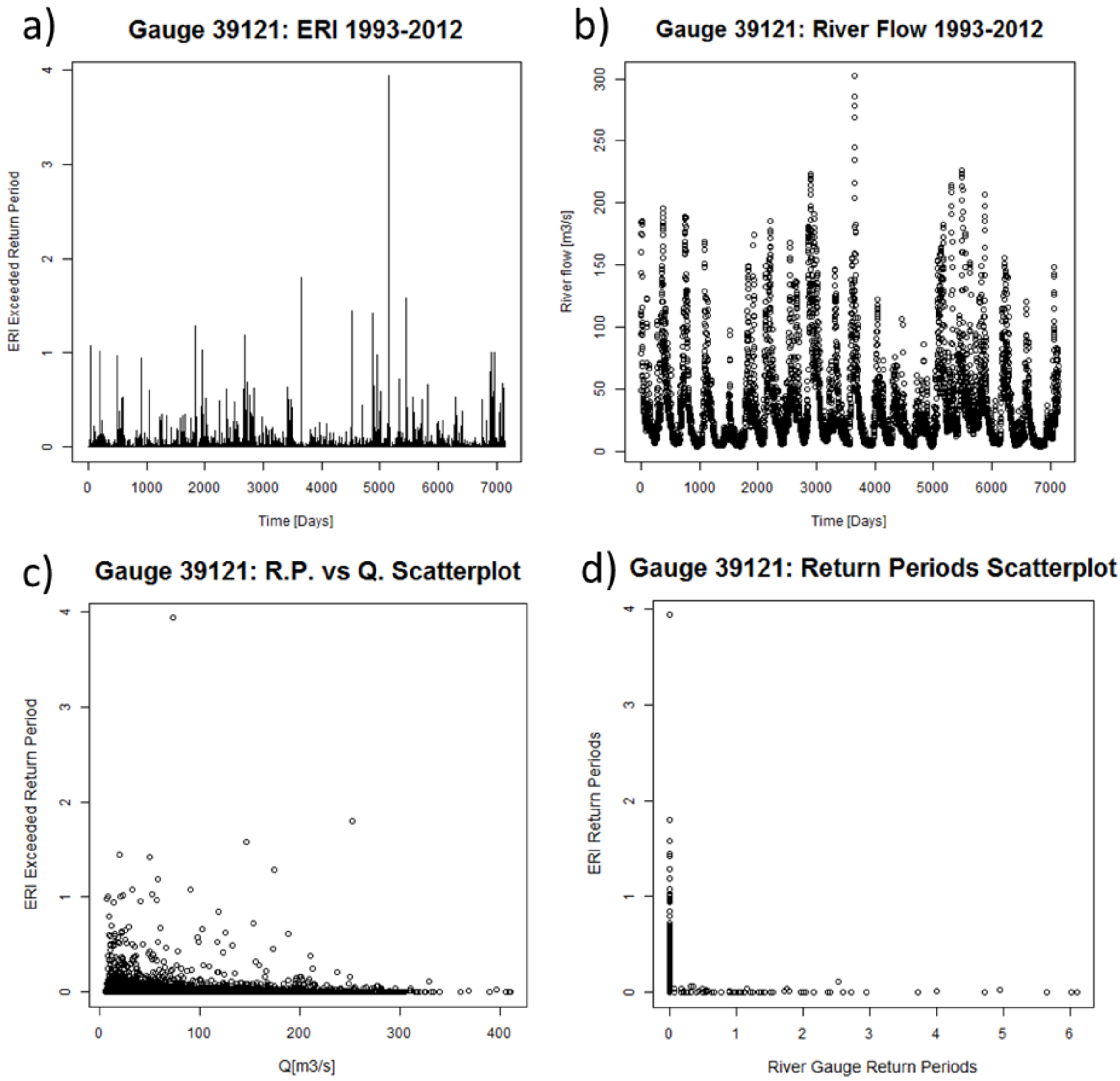

Figure 4.6 Comparison of modelled ERI return periods and observed river flow, for gauge 39121 (Thames – Walton)

Notes: The comparison was performed for the common available period (start 5 January 1993 00:00, end 23 July 2012 00:00).

Interpretation

Figure 4.6a displays time series from the ERI long-term climatology. It is an indication of extreme run-off values – larger values on the y-axis correspond to exceedence of higher ERI return periods. In Figure 4.6b, time series of river flow are displayed for the same period of time. Figure 4.6c correlates the 2 datasets. Finally, observed river flow time series were transformed into exceeded return periods and the comparison with the ERI exceeded return periods is plotted in Figure 4.6d.

Overall, there is a very poor correlation between the exceeded return periods based on ERI and those based on observed river flows (and also flow itself). As with the Cumbria case study discussed above, it was therefore decided not to calculate further regression models as they would have limited meaning. Similar outputs were found at all studied locations along the Thames.

EFAS historical analysis

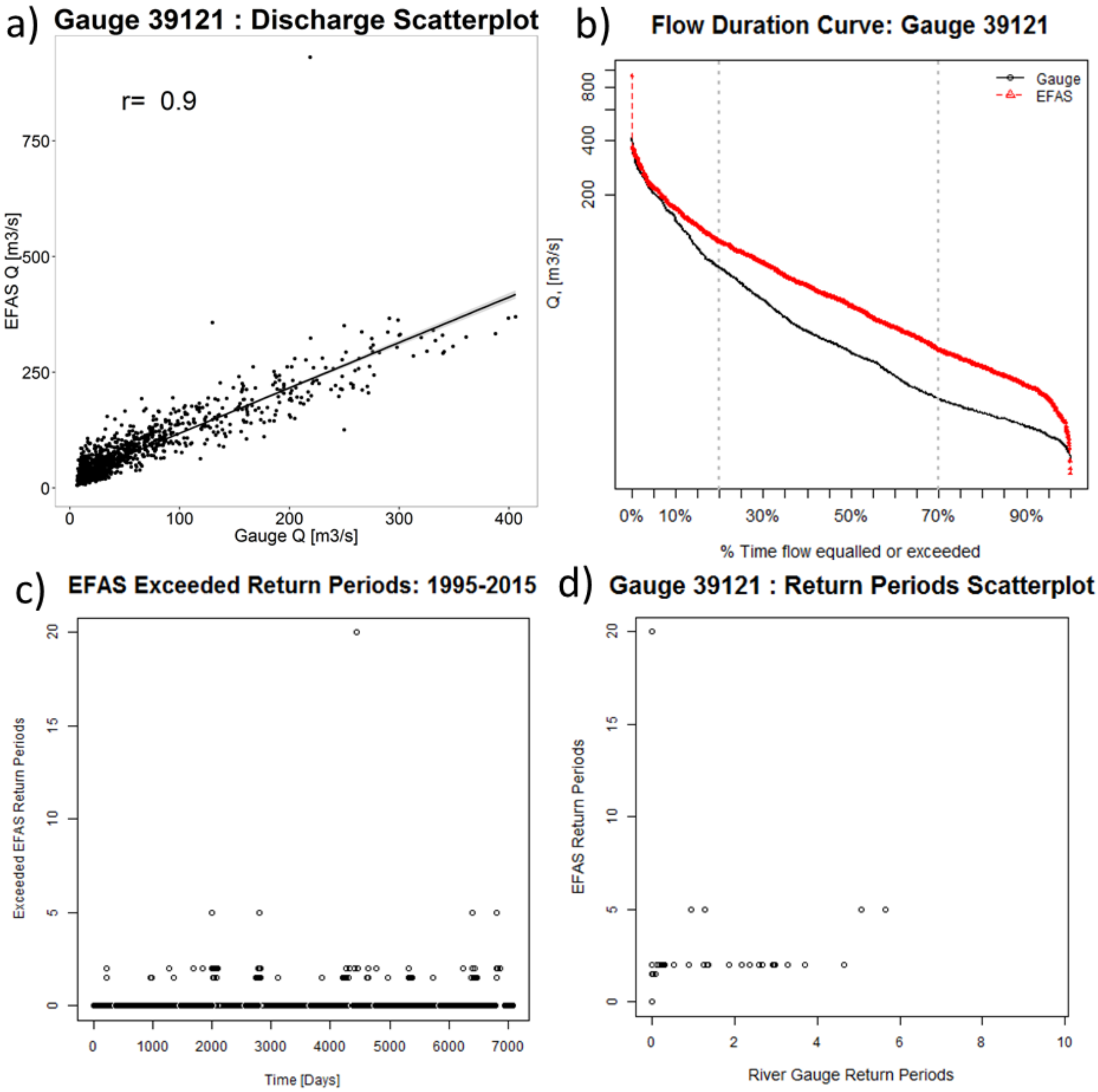

Figure 4.7 Comparison of modelled EFAS return periods and observed river flow for gauge 39121 (Thames – Walton)

Notes: The comparison was performed for the common available period (start 15 May 1995 00:00, end 8 March 2015 00:00).

Interpretation

Figure 4.7a correlates EFAS hindcast discharge time series and river flow time series. Compared with the scatterplot shown using the ERI return periods (Figure 4.5d), EFAS better reproduces river flow at this location. This is also shown by the comparison between flow duration curves of Figure 4.7b.

EFAS discharge values were transformed into exceeded return periods based on pre-computed values of threshold exceedances (1.5, 2, 5 and 20 year return periods) as shown in Figure 4.7c. The most important difference between this approach and river flows is that EFAS values are only reported when they exceed specific thresholds and thus do not provide a continous time series. Figure 4.7d correlates the available EFAS and river gauge time series where return periods are exceeded.

Overall, the model performs well for the River Thames, especially at locations situated further downstream and on the main river. This is expected due to model resolution and hydrological model specifications behind EFAS. However, the regression models obtained from the comparison between EFAS and river flow return periods are relatively linear; Figure 4.7d shows that the EFAS return period is not particularly sensitive to the river gauge return period. This is partly because the EFAS data are provided only when it has exceeded the threshold of the 2, 5 or 20 year return period.

It is noteworthy that the outlier present on these graphs, which shows extremely high EFAS flows and return periods belongs to the values exceeded on the 21 July 2007 forecast. This is also shown at at gauges 39001, 39072, 39111, 39121 and 39130.

4.2.3 Near real-time 10-day NWP forecast (An. 4)

ERI near real-time forecast

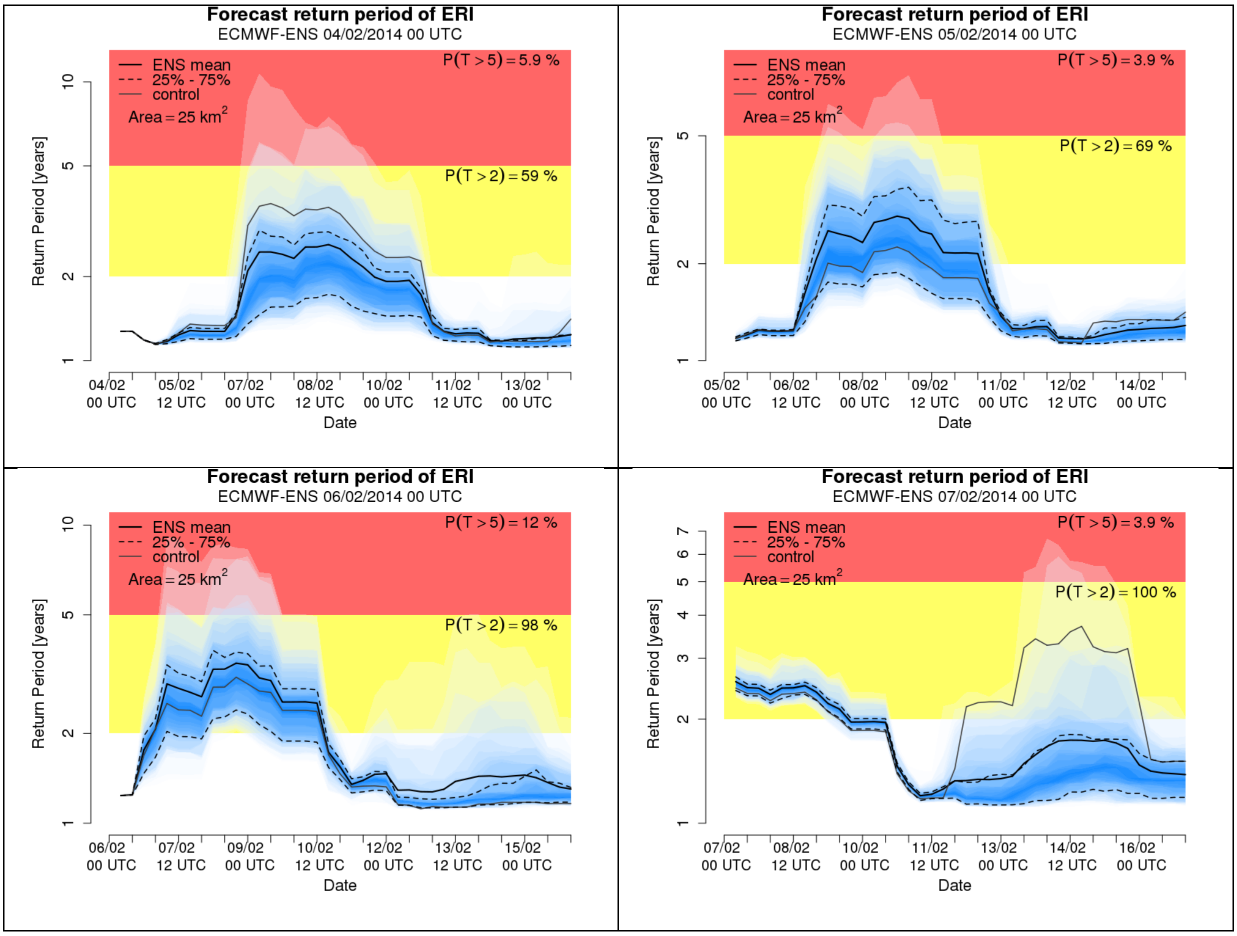

Figure 4.8 ERI forecast evolution on 4, 5, 6 and 7 February 2014 00 UTC at gauge 39121 (Thames – Walton)

Interpretation

ERI forecasts provide probabilistic information (51 ensemble members) of extreme run-off up to 10 days in advance of an event. As with EFAS, ERI provides results for 3 fixed thresholds based on simulated 2, 5 and 20-year return period events.

Looking at the forecast for 4 February 2014 for this location (gauge 39121), there is a medium to high probability of exceeding the 2-year return period threshold and a low probability of exceeding the 5-year return period threshold during 7–10 February 2014. In the following forecasts, the probabilities of exceeding these 2 thresholds increased. Higher confidence is seen in the 7 February forecast, where all ensemble members agreed on the return period exceeded. This flood event (7–10 February) would have been classified as a 2-year return period according to ERI.

From this analysis, it can be concluded that ERI forecasts are valuable for their intended purpose – as a probabilitic extreme run-off index with a 10-day forecast window. However, in terms of absolute return period values, they did not accurately capture the full magnitude of this flood event, as shown when comparing them with ground observations. The analysis in Section 4.2.2 suggests that a comparison of ERI return periods with river flow return period might not be straightforward.

Since September 2015, a new flash flood index, ERIC, has been operational within EFAS. Further information is provided in Section 6 of this appendix, as this has the scope for further development.

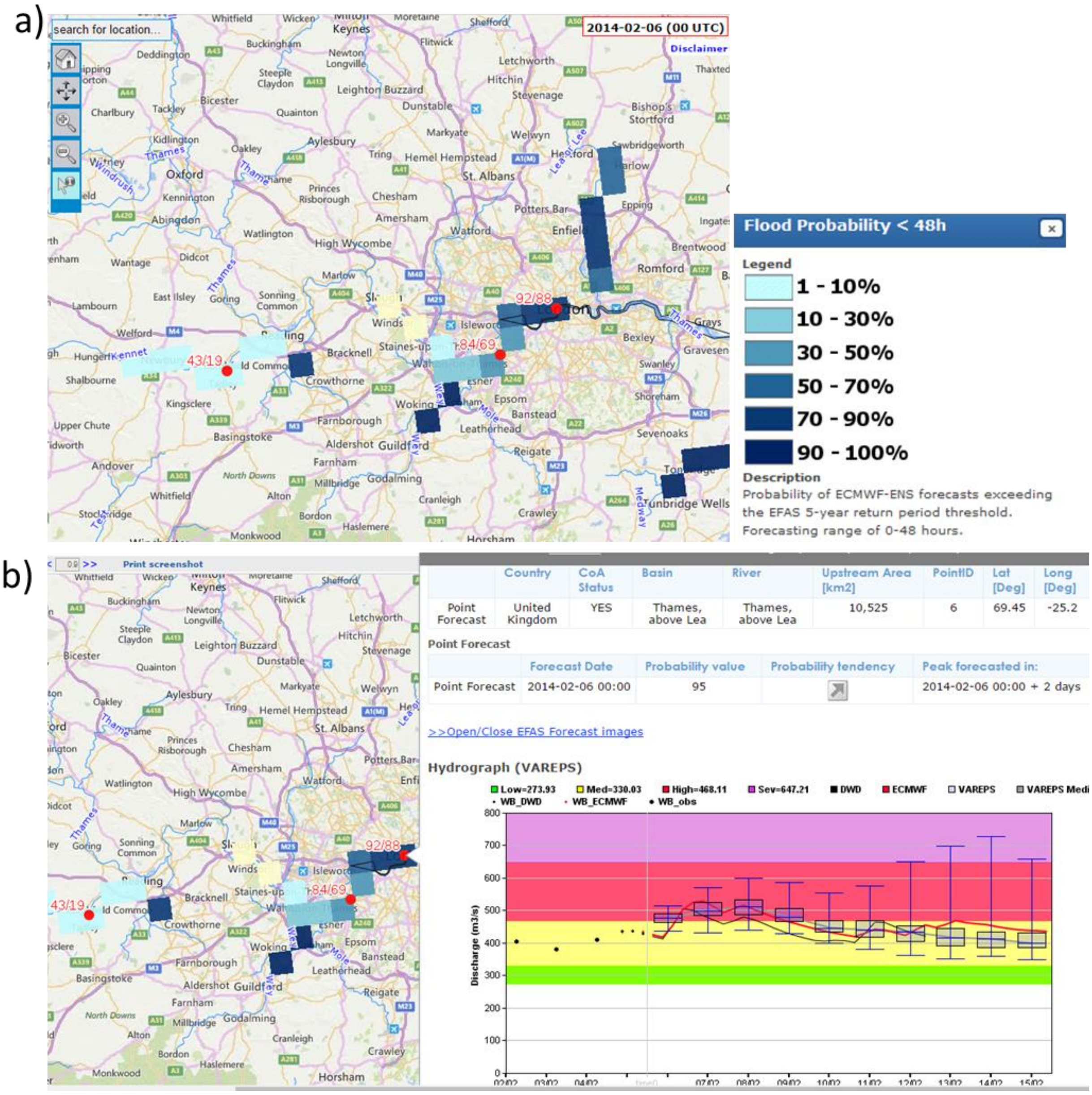

Figure 4.9 EFAS forecast on 6 f February 2014 00 UTC at gauge Thames – above Lea (further downstream of the study area)

Interpretation

EFAS uses multiple weather forecasts and ensemble prediction systems as inputs. Its forecasts are based on 2 deterministic, medium-range forecasts from ECMWF and the German Weather Service (DWD) – and thus different models.

Forecasts are also provided for 2 sets of ensemble prediction systems. The first is from ECMWF and covers medium-range lead times up to 15 days globally (with a spatial resolution of ~30km and 51 members). The second is provided by the Consortium for Small-scale Modelling (COSMO), a limited area model ensemble prediction system covering most of Europe, with a shorter range up to 5 days (with a spatial resolution of 7km and 16 members).

For the study period (7–17 February 2014) and river reach, EFAS forecast a potential flood event. The images in Figure 4.9 show a screenshot from the EFAS website for the 6 February 2014 00 UTC EFAS forecast. Figure 4.9a shows the flood probability in the 0–48 hours range. A hydrograph of the forecast at the most downstream location available within this area is also presented. For this forecast, the probabilities are highly variable along the River Thames. No specific EFAS floods or flash flood alerts were sent out to EFAS partners (EFAS 2014b) because the forecasts were not very persistent.

Nevertheless, for the River Thames at 'Thames above Lea', 5 flood alerts were send during the December 2013 to January 2014 period (EFAS 2014c). The dissemination procedure for this catchment is that EFAS alerts are sent direct to the Flood Forecasting Centre (FFC) and, along with the EFAS website information, are used to compile a 'Hydrological Assessment'.

4.2.4 Relationship between NWP forecast and potential flood impacts (An.5)

Methodology

Option 1: Use of the RoFRS dataset (In.6)

The proposed methodology links near real-time NWP forecasts to maps showing vulnerability to flooding. As the analysis has shown, there are difficulties in calculating accurate relationships between return periods (in ERI or EFAS) and those used in existing flood impact mapping, mainly due to differences in the approach to how return periods are derived. With further research, however, this has the potential to link broad-scale flood indices like ERI and EFAS to information on flood impacts.

The ERI extreme run-off forecast was taken as an example of NWP forecasts. For vulnerability and impacts, the RoFRS dataset was used. The aim was to develop a relationship between vulnerability levels (here, defined as economic damages and number of properties affected from the RoFRS) and the severity of the probabilistic flood forecasts). However, this methodology could be tested with alternative forecast and impacts datasets in future.

It was identified that a useful relationship between the run-off forecasts from ERI and the likelihood categories provided from the RoFRS dataset, required a regression model between the observed river flow level or discharge, and the simulated ERI surface run-off time series at each location, if available (see example in Figure 4.10a). Another approach is to directly link the ERI exceeded return periods to the return period exceeded at each flow gauge location. Return periods of gauged flows are typically derived by analysing historical flow records and applying statistical methods, as in the Flood Estimation Handbook.

The proposed methodology to link NWP forecasts to flood mapping is applied once the return period relationship is established. It can be used with either approach. For demonstration purposes, 'made up' data are used to outline the method here. However, the first part of the analysis is shown in Section 4.2.2.

This PoC study used a method (Environment Agency 2011, Keef et al. 2013) employed in the H21 Evidence Update for National Risk Assessment 2016 project. A look-up approach based on the Flood Estimation Handbook catchment descriptors was used to establish a relationship between river flow measurements at selected (gauged) locations and the equivalent exceeded return periods. Where a location is not available on the pre-computed look-up table, the nearest (linear) interpolation point is used to extract the flow/return period relationship. This process is shown in Figure 4.10.

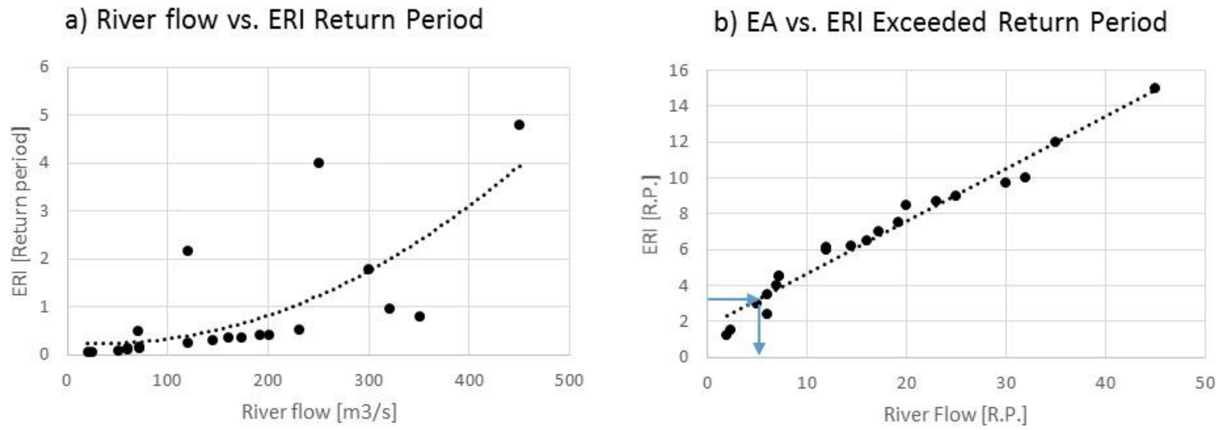

Figure 4.10 Regression model between (a) the ERI return periods and the river flow (m^3/s) and (b) ERI and river flow return periods at a river gauge 'X' using made-up data

Next, a flow duration curve type graph is built which relates vulnerability or exposure layers and the ERI return period exceeded. The idea is to calculate the flow corresponding to a given forecast (for example, ERI or EFAS), and relate this to the spatial exposure data via the return period estimated for that flow. A pre-computed look-up relates return periods to flow. These are then linked to the spatial exposure maps with the associated return period (which may involve some interpolation). It will also be necessary to make a spatial relationship between gauges and the forecasting product grid to ensure appropriate flood maps are selected on the basis of flow estimates at gauges.

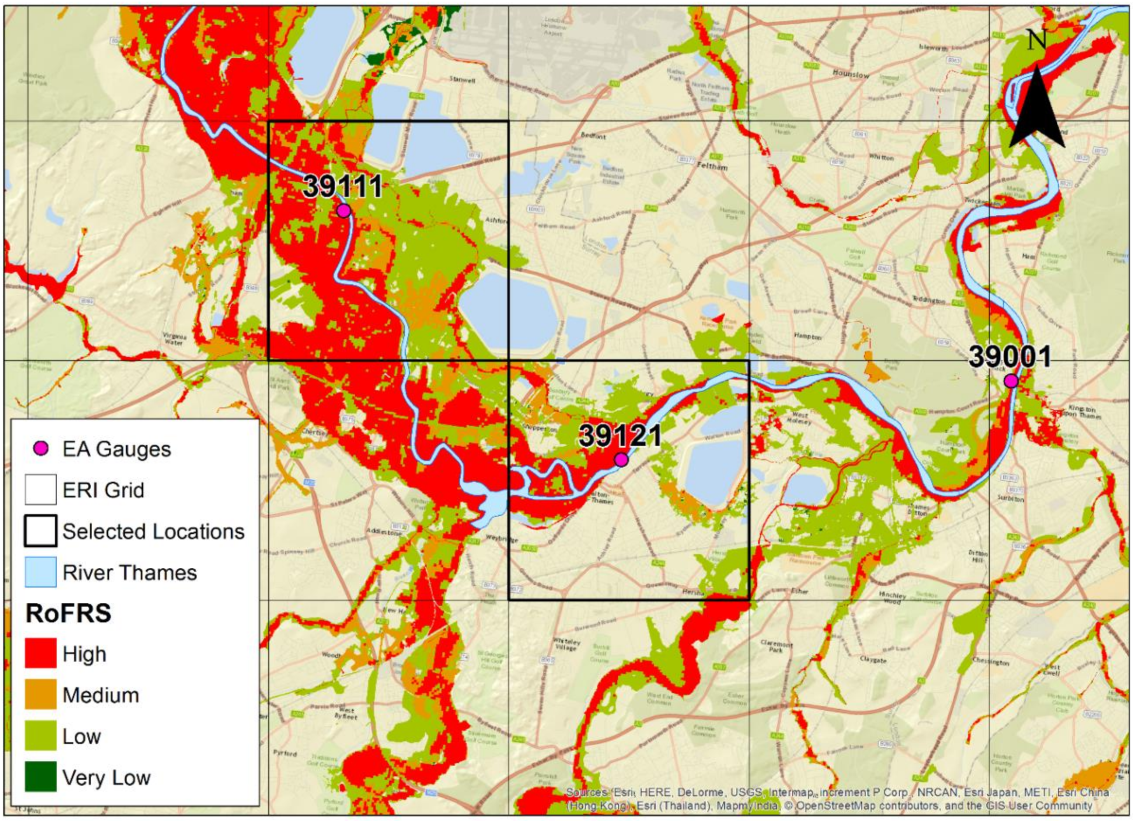

Figure 4.11 Example of ERI grids, Environment Agency gauges (pink dots) and 4 risk classification bands for the RoFRS layer for River Thames

Data needed

Observed river flow

At selected gauges, access to the NRFA time series would be required. Access to the full time series is recommended, including the study flood event if available. If available, flow duration curves would also be very useful.

ERI (or other forecast product) simulations

If available, the approach would use data from the 20-year climatology of surface run-off, which uses the unperturbed run of the ensemble prediction system (that is, the forecasts from a 51-member ensemble NWP). To ease data transfer, data could be requested at each grid point of interest (where an Environment Agency gauge is present). The continuous time series of surface run-off would be required. An alternative would be to request the continuous time series of the return period values exceeded (that is, run-off calibrated into ERI return period) for the unperturbed run of the ensemble prediction system. ERI forecasts for the Thames, Cockermouth and Storm Desmond flood events are already available.

RoFRS

This was previously known as the NaFRA Spatial Flood Likelihood Category Grid. It is a national assessment of flood risk for England which incorporates local expertise and data where available.

The dataset shows the chance of flooding from rivers and/or the sea, based on cells of 50m. Each cell is allocated one of 4 flood risk categories, taking into account flood defences and their condition. Two categorisations of risk are used, based on either 4 or 7 likelihood bands:

- 4 bands (Prob_4Band): high, moderate, low and very low RoFRS
- 7 bands (Prob_7Band):
  - greater than 1 in 10 years (>10%)
  - lower than 1 in 10 and greater than 1 in 30 (10% to 3.3%)
  - lower than 1 in 30 and greater than 1 in 75 (3.3% to 1.3%)
  - lower than 1 in 75 and greater than 1 in 100 (1.3% to 1%)
  - lower than 1 in 100 and greater than 1 in 200 (1% to 0.5%)
  - lower than 1 in 200 and greater than 1 in 1,000 (0.5% to 0.1%)
  - lower than 1 in 1,000 year probability (<0.1%)

However, for the case studies in this PoC, it was difficult to derive a strong relationship between the forecasted return period and the derived return period from river flow observations. These results therefore do not provide a straightforward link to the RoFRS likelihood bands to make it possible to make a real-time rapid assessment of the economic damages and counts of affected properties based on flood forecasts. Further research is recommended (for example by enlarging the sample of locations) to potentially establish a connection between both datasets.

Alternative options using the return periods interpolation (In.7 and In.8)

Interpolation of return periods along the river network provides many possibilities for real-time flood inundation impacts mapping. It is much more straightforward to interpolate return period along the river network and then look up a local value of flow or water level at each asset from pre-existing look-up tables than trying to model the actual flow/level values along the river network.

Two of the options that make use of this approach are the simulation library PoC (In.7) and the simplified fluvial modelling PoC (In.8). For further information, please refer to their pro-forma reports presented in Appendix 6 and Appendix 5 respectively.

5 Implementation considerations

This section presents items to be considered by the Environment Agency if this PoC option is developed further towards operational use.

Section **Error! Reference source not found.** details technical considerations (input data, intermediate processing and outputs provided) beyond the specifics of the PoC testing undertaken by this project. The flow chart from Section 2 showing the steps involved in running the system is reproduced as Figure 5.1. Each step is discussed in turn.

Section **Error! Reference source not found.** discusses the skills, cost and effort that might be required to implement and maintain the system.

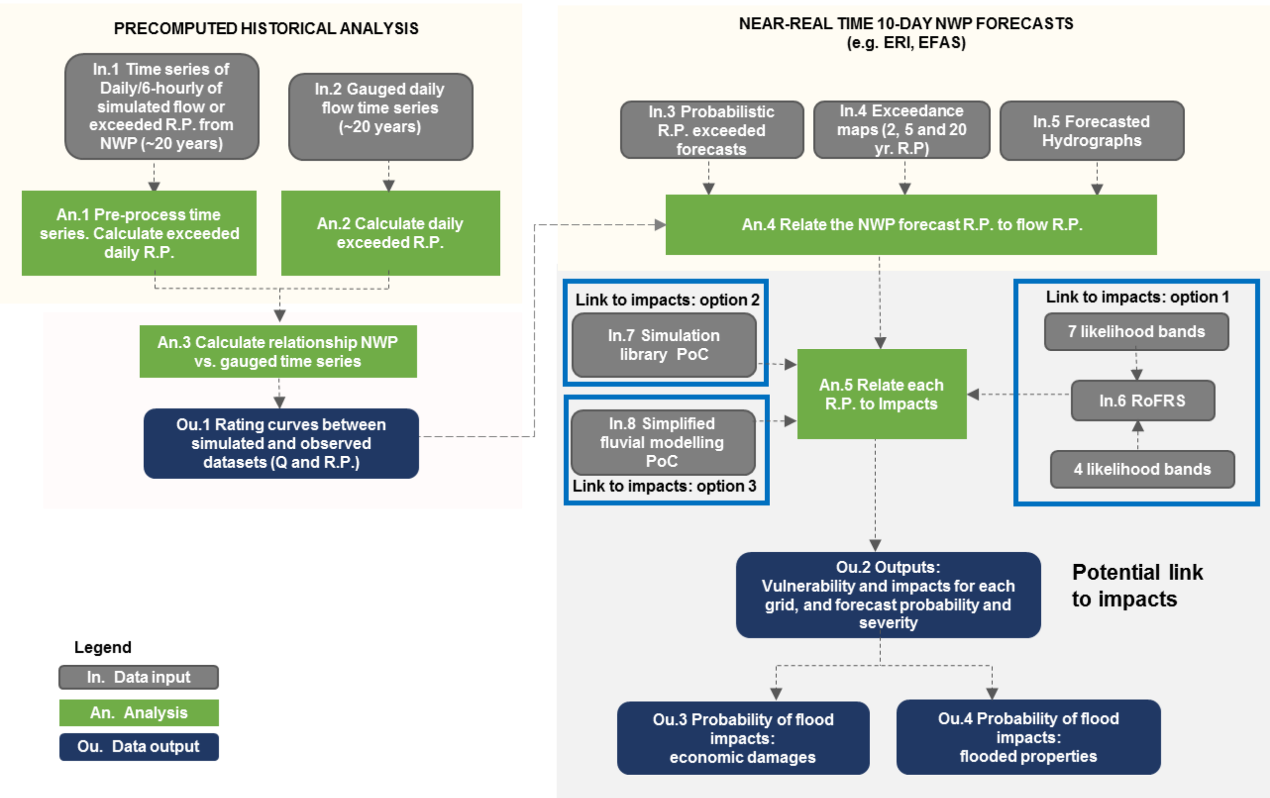

Figure 5.1 Flow chart showing PoC workflow for 10-day lead time NWP products

5.1 Operating the system

Table 5.1 Key considerations in using this option within an operational forecasting system

Description	Priority
Integration within Environment Agency systems (for example, general adapters or APIs required to interact with the data).	High
Operational transfer of datasets (NWP forecasts) from ECMWF to the Environment Agency, up to twice per day, to calculate near real-time exceeded return periods and related impacts.	High

Description	Priority
Agree on consistent terminology for flood probabilities. For example, between ‘return periods’ provided by ECMWF and ‘Annual Exceedance Probability’ reported by Environment Agency. It may also be necessary to translate ECMWF model outputs to ‘Annual Exceedance Probability’ terms, where required.	High
Post-processing of model outputs will require R and GIS routines to intersect flood forecast with receptors (for example, properties).	Medium

Table 5.2 Detailed considerations for the near real-time operational steps

<table>
<tr><th colspan="2">In.4. Input data (forecast flows or run-off severity)</th></tr>
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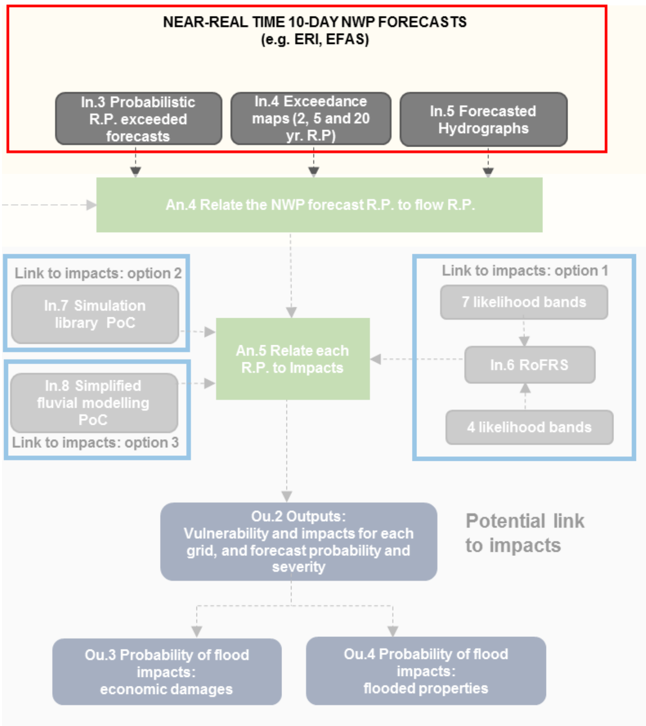


</td></tr>
<tr><td>Description</td><td>10-day flood forecasts derived from NWP forecasts are the main input required for this option. To optimise this process, a group of locations can be pre-selected.

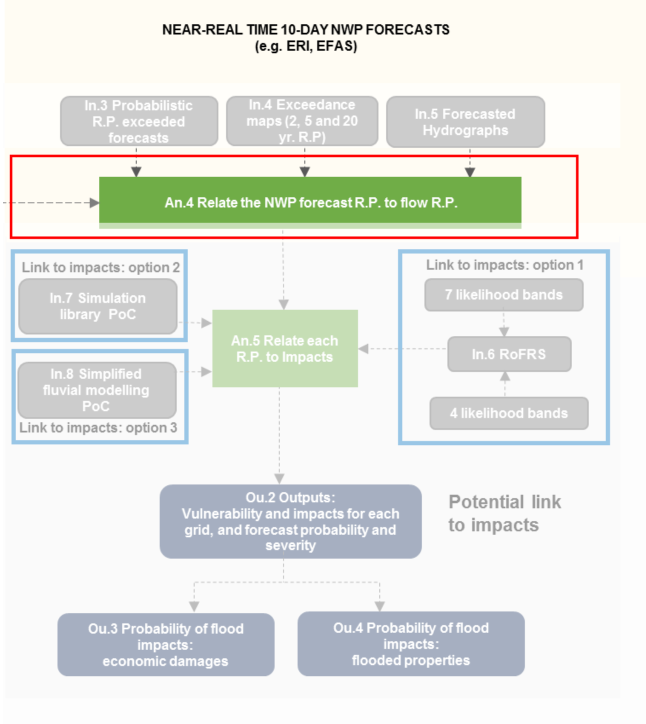
Hydrographs will be useful to visualise at a certain location the 10-day outlook. This could be obtained through the website (if available) or sent by the provider.</td></tr>
<tr><td>Data overheads</td><td>Low – if text files are provided at specific locations, as are typically small (a few MB).

Medium – if maps and hydrographs are provided.

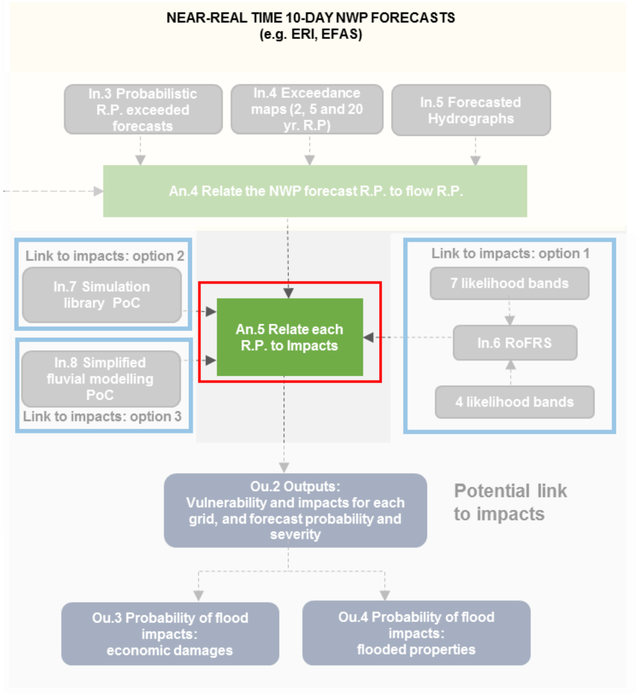
With multiple forecasts (for example, twice a day), a larger data storage will be needed.</td></tr>
<tr><td>Run times</td><td>The forecasts are run every 12/24 hours at ECMWF. Long run times are avoided by using the outputs of the NWP.</td></tr>
<tr><td>Software</td><td>An FTP (file transfer protocol) site will need to be created and an automatic file transfer mechanism put in place.</td></tr>
</table>

Hardware	Not applicable

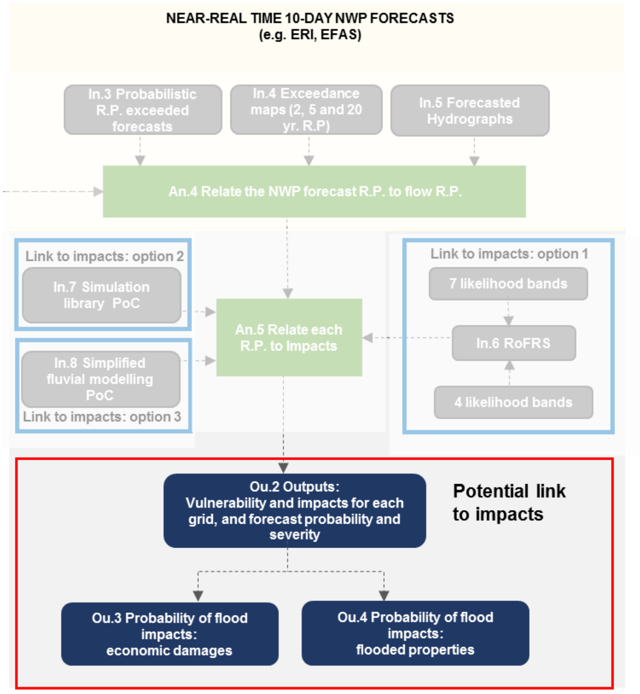
In.4. Input data (forecast flows or run-off severity)



Description	Near real-time forecasts are related to observed flows through the regression models and plots obtained in the historical analysis. Ideally, this uses exceeded return periods from the forecasts.
Data overheads	Low – for a single time interval. The amount of input data used for this analysis is generally small.
Run times	Low – once the automatic script to ingest the data and calculate the relationship is created, run times are low.
Software	Currently, the script has been implemented in R software on an online testing mode (not operational). It can be rewritten to other programming languages.
Hardware	Not applicable

An.5 Relate each return period from flood forecast to impacts	
	
Description	Post-processing of forecasted flood severity and exposure or vulnerability datasets Intersecting location of flood forecasts with receptor data (for example, properties)
Data overheads	Low – for a single time interval. Has potential to be higher for multiple time intervals.
Run times	Low – once the automatic script to ingest the data and calculate the relationship is created, run times are low.
Software	GIS software is required to post-process model outputs with receptor data. .shp files can be read, processed and analysed by ArcGIS and time series (for example, csv, .txt) by R.
Hardware	Not applicable

Ou.2,3,4 Flood impacts: economic damages and flooded properties



Description	Counts and areas with economic damages and property datasets impacted by floods, typically in GIS format, tables and output plots
Data overheads	Low – for a single time interval. Has potential to be higher for multiple time interval.
Run times	Low – for post-processed outputs
Software	Not applicable
Hardware	Transmitting information on flooded assets may require transfer of smaller volumes of data back to a final operational system.

5.2 Implementation and ongoing maintenance of an operational system

Table 5.3 Summary of implementation and maintenance issues for an operational system

Overview
This option reuses outputs from existing flood forecasting system and indexes. Limited additional skills or training should therefore be required to transfer the data outputs and implement the analysis. However, Environment Agency forecasters may need some training to: • understand and correctly use the ECMWF products • translate information between return periods and probabilities • manage several different forecasting products • interpret uncertainty/use of ensembles for flood forecasting (only deterministic

outputs are typically available at present)			
Implementation			
Change required	**Low**	Moderate	Significant
	The option could be implemented within existing forecasting systems. Some change would be required to disseminate real-time flood mapping and impact data.		
Cost to implement	**Low**	Moderate	Significant
	The Environment Agency already has free access to EFAS. However, the real-time data are only accessible by authorised partners such as the Environment Agency. The cost associated with transferring these data would be relatively low.		
Skills required to implement	Limited additional training or skills would be required to implement this option. Some R knowledge will be needed to adapt the scripts.		
Time/effort to implement	The R routine and ArcGIS task could be implemented using exiting scripts and methodology developed during this PoC.		
Ongoing maintenance			
Difficulty in accommodating change	**Low**	Moderate	Significant
	The option would need to accommodate: • updates to impact mapping models (for example, RoFRS) • updates to model (forecasting) changes • extension of time series from gauges and historical forecast to update regression models		
Cost to maintain	**Low**	Moderate	Significant
	ArcGIS software packages require ongoing licensing. Other GIS software can also be used. The ERI/EFAS forecast is provided without a licence for the Environment Agency as a partner. R is open source software.		
Skills required to maintain	Limited additional training or skills would be required. The most important skill set is in interpreting the information of the probabilistic ensemble forecasts and using this to inform decision-making during an event.		
Further consideration and challenges	• Potential overlap and inconsistencies with the strategic hydrometeorological forecasting products and services provided the FFC based on Grid-to-Grid (G2G) modelling. • The mismatch in return periods/probabilities between ECMWF products and those estimated by other means. The 2 are very different and could cause confusion. • Uncertainty/use of ensembles is very much embedded in the ECMWF products. An appreciation of uncertainty is very important for some users but could confuse others. • A better understanding and clear guidance will be needed to		

	select the most appropriate ECMWF product for certain catchments and types of flooding in the UK.
Time/effort to maintain	The R routine and ArcGIS tasks could be implemented based on exiting scripts and methodology developed during this PoC. However, further development and testing would be required to set up these scripts in an operational manner.

6 Scope for further development

Table 6.1 Future data and model improvements that may benefit this option

Description	Impact	Recent examples
Update regression models or relationship plots after NWP updates (for example, after a model calibration round) Updates of river flow time series might also be needed.	Improvements to prediction accuracy	Outputs from a new EFAS calibration round were implemented in 2016.
Updates to exposure and vulnerability datasets to be incorporated allowing improvements to accuracy of impacts	Improve representation of impacts	Update from the NaFRA to the RoFRS dataset
Testing and incorporating the latest developed NWP at ECMWF (within EFAS) – for example, incorporation of ERIC (Raynauld et al. 2015), a new European flash flood index that has run operationally within EFAS since September 2015	Improved ability to capture flash flood events and to relate this forecasts to impacts	Figure 6.1 shows an example of the performance of ERIC and EFAS during the floods in December 2015.
Testing the methodology presented in the PoC, along with the several NWP products, on additional case studies	Provide further information on the strengths and weaknesses of the approach	2015 Cumbria floods for future testing
Testing the use of the simulation library PoC and/or the simplified fluvial modelling PoC approaches to establish a link to potential flood impacts	Predict near real-time potential impacts caused by floods (for example, properties, economic damages)	See the corresponding PoC pro-formas for further details on the methodology (Appendix 6 and Appendix 5 respectively).

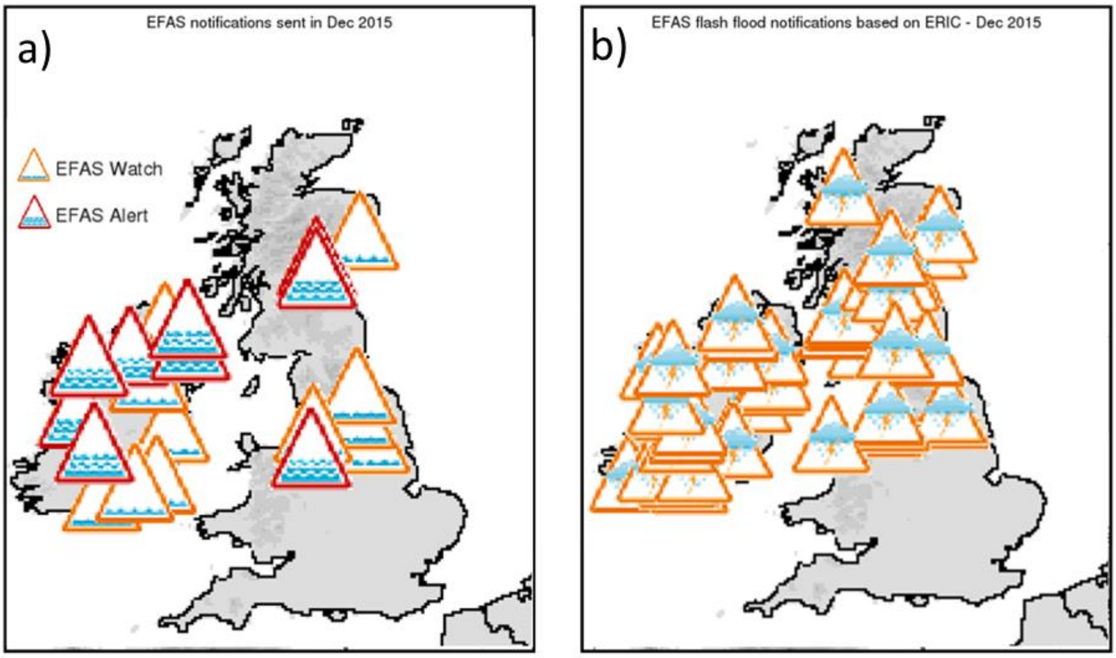


Figure 6.1 EFAS and ERIC examples during the UK floods in December 2015: (a) EFAS flood alerts and watches and (b) flash flood reporting points

Source: EFAS (2016)

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