Surface Water Flood Forecasting

Flood Forecasting on Trunk Roads

Transport Scotland

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Executive Summary

Flooding on the trunk roads network in Scotland have significant disruption and costs to economy and society, as well as being a cause of potential roads infrastructure damage during severe flooding events. According to the new UK Climate Projections released in 2018 by the Met Office & Environment Agency, Scotland in particular has had an 11% increase in average annual rainfall over the most recent decade, with projections of even greater rainfall intensity and duration which can contribute to more flooding events.

Fluvial and coastal flood forecasting approaches have been traditionally employed in Scotland to mitigate the effects of flooding in areas that interact with fluvial or tidal reaches, however surface water forecasting is not as well researched or trialled due to the complexity of this type of flood modelling. A trial of this was conducted by SEPA’s Scottish Flood Forecasting Service on a small study area in Glasgow during the 2014 Commonwealth Games held in the city, with a successful outcome of providing adequate warning for anticipated surface water flash flooding with a 24 hour lead time.

Atkins was appointed by Transport Scotland to investigate the feasibility and benefits of a pluvial flood forecasting system for the trunk road network. This comprised of a literature review of published research on flood forecasting system case studies in the UK and worldwide, an assessment of the methodology and lessons learned from the 2014 Commonwealth Games flood forecasting as well as a desk study using data supplied by Transport Scotland to determine trial areas for where such a tool would be of most benefit.

A GIS methodology was applied for the hotspot analysis with data provided by Transport Scotland from an in house tool called Disruption Risk Awareness Tool (DRAT) as well as historical incident data from roads Operation Companies that are responsible for the maintenance of the trunk roads network. These datasets were geolocated and compared against the SEPA national pluvial flood hazard maps and mapping provided from a previous study by AECOM on the impact of climate change on Transport Scotland’s roads network. Road gradient data was used to determine where pooling was likely to be most severe. Ten locations were identified as areas that would have a high likelihood of being impacted by surface water flooding from this analysis.

The main conclusion reached from the subsequent literature review of international and local case studies of roads flood forecasting showed that there is no precedent for large scale pluvial flood forecasting due to the localised nature of flood events. Localised early warning systems are in use in multiple countries, primarily in urban hotspots and using on-site telemetry which can be a costly in terms of up-front capital outlay and ongoing maintenance costs. Examples of large scale pluvial flood modelling for flood forecasting are lacking, and small scale models can be processor and data hungry as modelling for this can be complex. Examples of pluvial flood modelling is often not real-time, and sufficient past flood data or local knowledge is required for calibration to ensure model accuracy.

The 2014 Commonwealth Games flood forecasting was also observed to be of a small study area, with intensive skilled manpower, data and IT infrastructure as well as coordinated communication efforts between all stakeholders for the event. This study concludes with some actions and recommendations for Transport Scotland to define a scope and a strategy for implementing a surface flood forecasting tool, given the common limitations and required inputs from case studies of such forecasting systems. Data collection specifications, data requirements and consultation with other stakeholders, targeted decision making on level of investment into such a tool and further research on appropriate communication methods for an Early Warning System are recommended to be able to create a system that would serve Scottish needs unique to its geography and climate for the future.

Glossary and Abbreviations

Abbreviation	Description
CEH	Centre for Ecology and Hydrology
CREW	Centre for Expertise in Water
DBFO	Design-Build-Finance-Operate
DMRB	Design Manual for Roads and Bridges
DRAT	Disruption Risk Assessment Tool
EWS	Early Warning System
FEWS	Flood Early Warning System
FREWS	Flood Risk Early Warning System
FRM	Flood Risk Management
GIS	Geographic Information Systems
NWP	Numerical Weather Prediction
OC	Operating Companies
SEPA	Scottish Environment Protection Agency
SRRB	Strategic Roads Research Board
STEPS	Short Term Ensemble Prediction System
NERC	National Environment Research Council
NFRA	The National Flood Risk Assessment
TS	Transport Scotland
UKCP18	UK Climate Projections 18
UKV	UK Variable

1. Introduction

Transport Scotland through the Strategic Roads Research Board (SRRB) appointed Atkins Limited to determine the merit and benefits of a flood warning tool that can be applied to surface water flood hazards on the trunk road network.

The aim of this study is to:

- Understand the flood risk to the current Trunk Road network from surface water flooding;
- Understand the operational response to flooding on the Trunk Road;
- Draw from experiences from the rest of the world;
- Investigate how an existing surface water forecasting system can be developed;
- Understand what information from a forecasting tool would be beneficial; and
- Make recommendation on the way forward.

A key element of the study has been engagement and collaboration with the Scottish Environment Protection Agency (hereon referred to as SEPA) Flood Unit. Their input, suggestions and contributions to this report have been very valuable.

Transport Scotland have provided the following data, which will be utilised as part of the study.

- SEPA Flood Maps;
- Operating Companies flood incident data for 2016-2018;
- Road gradients for the Trunk Road Network;
- Centre of Expertise for Waters (CREW) ,2015 Surface Water Flood Forecasting for Urban Communities report; and
- AECOM, 2016, Potential Impacts of Climate Change on the Trunk Road Network.

2. Background

2.1. Flood Risk Management Act, 2009

The impacts of flooding are well documented and are often devastating regarding the cost of repairs, replacement of damaged property and loss of business. The Scottish Government is working to create a sustainable approach to flood risk management and the impact of climate change, through the implementation of the Flood Risk Management (Scotland) Act 2009.

The Act introduces a sustainable approach to flood risk management taking into consideration the impact of climate change. It creates a joined up and coordinated process to manage flood risk at both national and local level. SEPA are the overarching authority and have a strategic role for flood risk management, including flood warning systems. SEPA are working closely with local authorities, Scottish Water, and other responsible authorities to deliver flood risk management planning in Scotland.

Transport Scotland is not specifically named within the FRM, however the Act requires all responsible authorities to act with a view to achieving the objectives set out in flood risk management plans, and to have regard to the social, environmental, and economic impact of the exercise of those functions in the Act. In particular, the act requires responsible authorities to deliver the following.

- Act in the way best calculated to manage flood risk in a sustainable way;
- Promote sustainable flood risk management;
- Act with a view to raising public awareness of flood risk;
- Act in the way best calculated to contribute to the achievement of sustainable development; and
- So far as practicable, adopt an integrated approach by co-operating with each other so as to co-ordinate the exercise of their respective functions.

Key outputs of the FRM act, which will enable a sustainable approach to flood risk are:

- Flood mapping of the hazards;
- National flood risk assessment; and
- Flood forecasting.

2.2. Flood Hazard Maps

A key milestone within the FRM Act was the development and production of flood hazard and risk maps. The maps include Fluvial, Coastal and Surface Water flooding, providing a likelihood of flooding from high to low. The maps are viewed as a tool to support flood risk management decisions, land-use planning and to help raise public awareness.

Flood risk is reported for the following incidences High, Medium and Low. Table 2-1 relates the scenarios to likelihood of flooding incidence.

Table 2-1 - Flood Risk Scenarios

Likelihood	Return period in years	Annual Exceedance Probability
Low	1 in 1000 chance	0.1
Medium	1 in 200 chance	0.5%
High	1 in 10 chance	10%

As part of this study Transport Scotland and SEPA provided access to the flood hazard maps, and these have been reviewed to understand the potential extent of surface water flooding on the trunk road network.

2.3. National Flood Risk Assessment

The National Flood Risk Assessment (NFRA) was the first step in developing a Flood Risk Management Strategy and Local Flood Risk Management Plans. The assessment increased the understanding of the sources of flooding and the impacts, allowing areas at the greatest risk to the impact of flooding to be identified.

As part of this assessment, the potential flood risk to transport infrastructure has been assessed by individual sources. Under a Medium likelihood scenario (1 in 200 year/0.5% AEP) it is estimated that approximately 559km of all roads are affected by coastal flooding, 866km of road is affected by fluvial flooding and 466km of road is affected by surface water flooding (SEPA NFRA, 2018).

2.4. Flood Forecasting

SEPA is Scotland's national flood forecasting and warning authority, providing coverage for 269 communities (SEPA Flood Forecasting Framework) with Figure 2-1 showing the current and proposed coverage, extracted from SEPA's 2017-2021 Flood Warning Development Framework. The existing flood forecasting systems primarily cover coastal and fluvial flooding. However, in 2014, SEPA's Scottish Flood Forecasting Service successfully piloted a surface water flooding forecast tool in conjunction with the Centre for Expertise in Water (CREW) based on SEPA's Regional Pluvial (rainfall-related) Flood Hazard maps. The tool was tested during the Commonwealth Games in Glasgow in 2014 to inform surface water flooding impact on the cycling road race. As a result, SEPA have produced the UK's first operational surface water flood risk forecast with a 24-hour lead time (predicting in real time). This tool only covers a relatively small urban area and ongoing research is required to extend coverage to more or larger areas. SEPA are currently commissioning their own research into flood forecasting for surface water flooding.

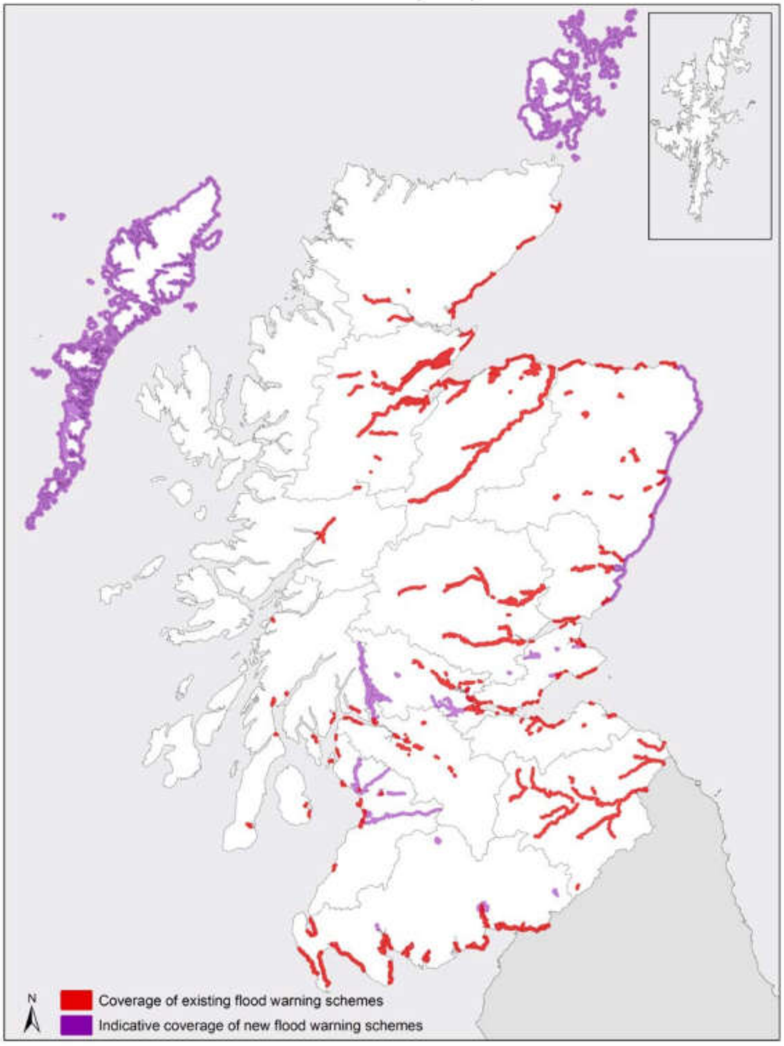


Figure 2-1 - Location of Existing and new Flood Warning Schemes

3. Flood Risk Impact to Trunk Roads

The NFRA Scotland highlights that the trunk road network is vulnerable to flooding from all sources (fluvial, pluvial, and coastal), with the trunk road and motorway network comprising of 3507km of road and roundabouts, an understanding of the risk and means to have a sustainable approach to flood risk is required.

Flooding can disrupt the operation of the road network with knock-on consequences for many social and economic functions (delaying deliveries, preventing or delaying people from accessing employment or disrupting vital healthcare services). Communities located in remote areas are particularly vulnerable to road network disruption as they rely more heavily on road transport than those living and working in other parts of Scotland and alternative routes (where these exist) often require long diversions. ClimateXChange provides independent advice research and analysis to support the Scottish Government as it develops and implements policies on adapting to climate change. The ClimateXChange have developed a series of indicators which are being used to show how Scotland is performing against its climate change objectives. The indicators include “Road network at risk of flooding”, Table 3-1 below, illustrates the scale of the flooding challenge with around 5% of the network directly at risk from fluvial flooding (river) and around 52% likely to be affected from pluvial (surface water) flooding. They also report that in 2014-2015 flooding was the fourth most common cause of trunk road incidents after broken down vehicles, road traffic accidents and damaged road or street furniture.

Table 3-1 - ClimateXChange Road Network at Risk of Flooding

Risk of Flooding from a 1:200 year event [1]	Road Type	Percentage at risk		
		Fluvial	Pluvial	Coastal
Directly	All	0.81	1.23	0.34
	Trunk	5.24	2.13	0.73
Would be affected	All	7.87	13.41	-
	Trunk	24.89	51.89	-

[1] The assessment of this indicator has been undertaken for 0.5% probability (1:200 year) flood events only.

An analysis of the Transport Scotland Operating Companies (OC) flood incident data confirms that a total of 1612 flooding incidents were recorded between 2016 and 2018, 11 of which resulted in road closure. Of the total records, 545 were attributed explicitly to flooding, with the words “flooding” or “flooded” used in the incident record description. A further 111 records used the word “blocked” in the incident record description, which may be indicative of incidents related to operational or structural issues with the road drainage system.

The analysis of this data shows that the worst-affected regions with most incidents appear to be South West and North East units, with a total of 566 and 532 incidents reported for these areas respectively. However, the areas with the largest sum attributed to flooding/flooded are in the North East and North West units, with 318 and 111 recorded incidents respectively. The distribution of incidents per region is shown in Figure 3-1 below.

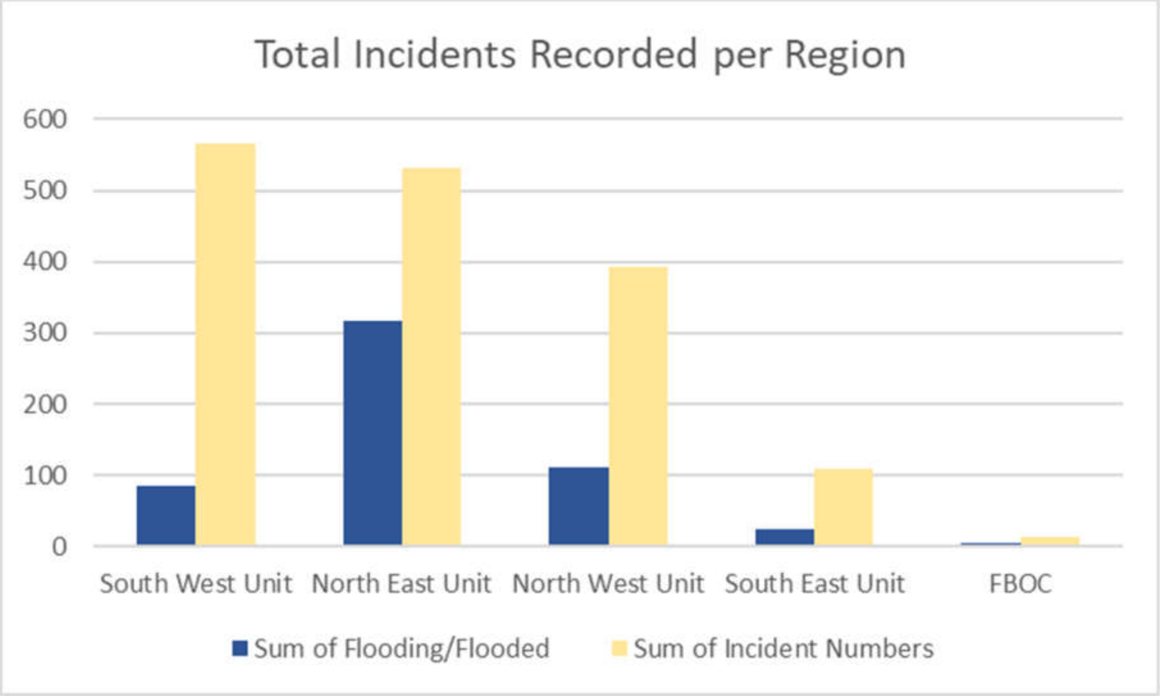


Figure 3-1 - Total Incidents Recorded per Region/Operating Company

Figure 3-2 gives an overview of the number of incidents recorded per trunk road in Scotland, with the worst affected road being the A90, followed by the M8, A82 and A85. Appendix 6.1.A.1 then breaks down the number of incidents as recorded by Transport Scotland since 2016 and the Met Office named storm incidents by road name. It also indicates the number of key words found in the descriptions from Operating Companies from each incident record.

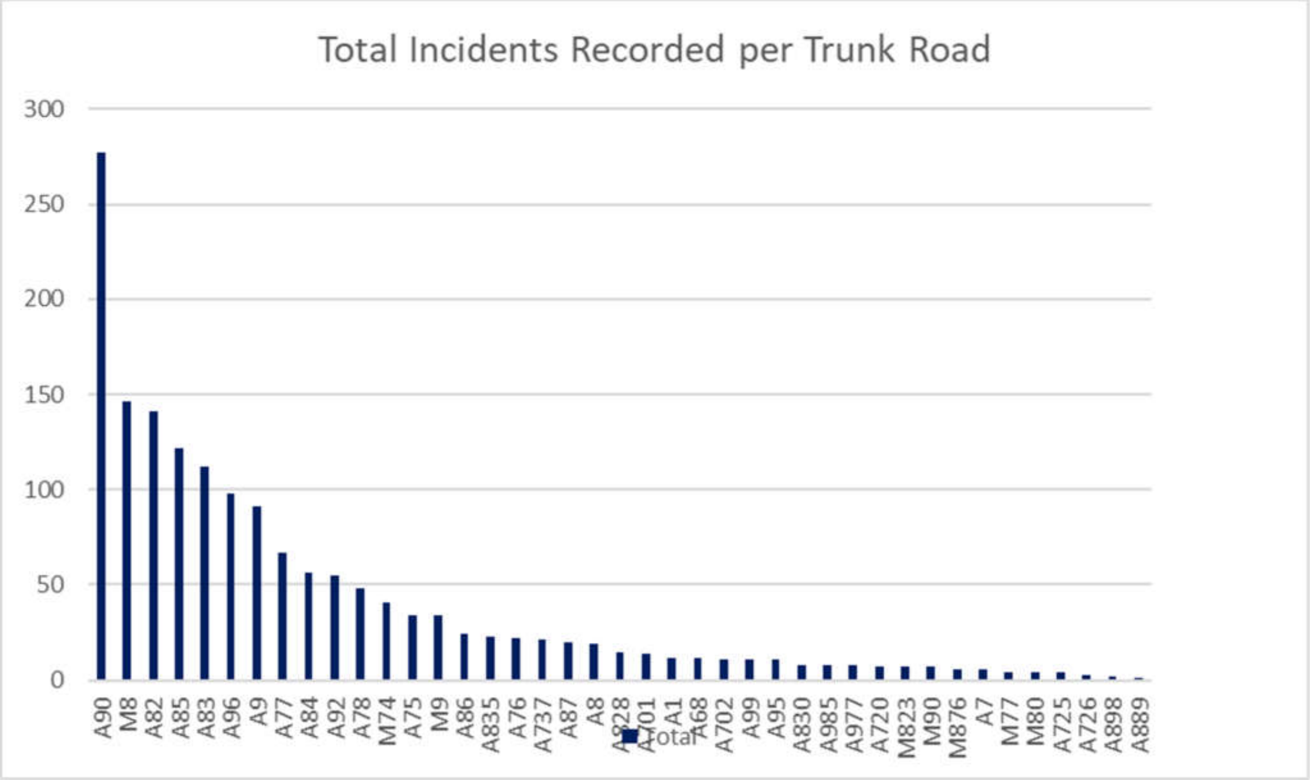
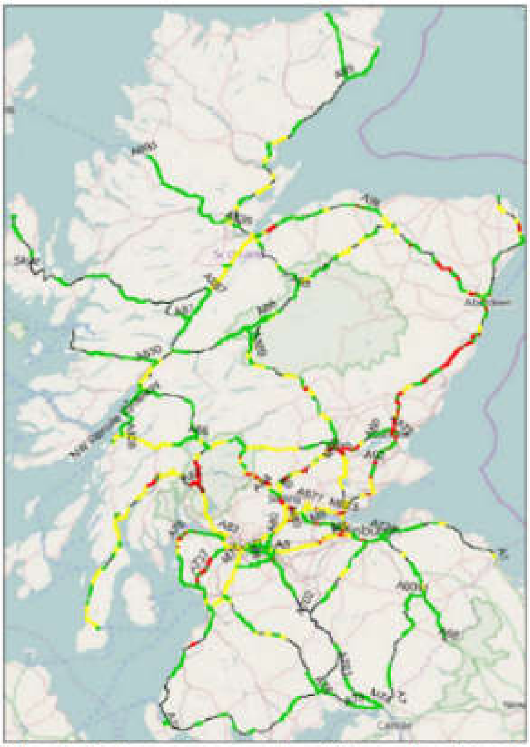


Figure 3-2 - Total Incidents Recorded per Trunk Road

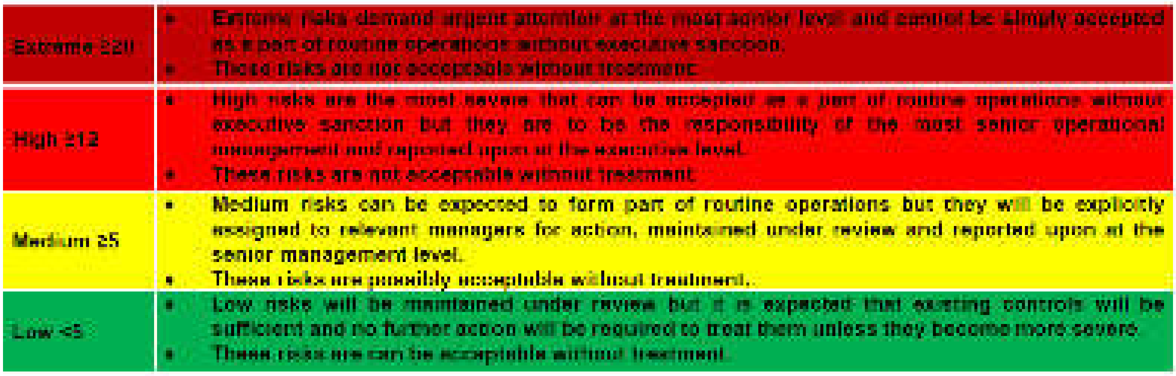
As part of the asset management approach to assessing flood risk management, the flooding incident database is used to inform the Transport Scotland Disruption Risk Assessment Tool (DRAT). The DRAT tool assesses the impact of disruption (including flooding disruption) using the following inputs.

- Type of closure;
- Duration of closure;
- Route Hierarchy; and
- Quality of Diversion Route.

An output from the DRAT tool is shown in Figure 3-3 below.



Flood risk assessment – TS road network



Extreme ≥20	• Extreme risks demand urgent attention at the most senior level and cannot be simply accepted as a part of routine operations without executive sanction. • These risks are not acceptable without treatment.
High ≥12	• High risks are the most severe that can be accepted as a part of routine operations without executive sanction but they are to be the responsibility of the most senior operational management and reported upon at the executive level. • These risks are not acceptable without treatment.
Medium ≥5	• Medium risks can be expected to form part of routine operations but they will be explicitly assigned to relevant managers for action, maintained under review and reported upon at the senior management level. • These risks are possibly acceptable without treatment.
Low <5	• Low risks will be maintained under review but it is expected that existing controls will be sufficient and no further action will be required to treat them unless they become more severe. • These risks are can be acceptable without treatment.

Figure 3-3 - DRAT Assessment Tool

Based on risk from the DRAT assessment the tool then identifies appropriate actions as follows:

- Exposure Reduction (Detect Notify Act);
- Hazard Reduction (Capital Works); and
- Monitoring and Further Investigation.

As part of this study we became aware Transport Scotland had commissioned AECOM to examine the potential impacts of climate change and severe weather on the Trunk Road Network, and to identify the most effective ways in which Transport Scotland can respond to these risks. The findings from the AECOM study will inform improvements in the Asset Management process and will be tested in the DRAT. As a 'next step', it was recommended that Transport Scotland undertake further work to identify and quantify the costs and benefits of adaptation measures to provide indicative information relating to the expected costs and benefits of specific responses. The key flood related findings of the AECOM report were as follows

- 76 trunk road network sections (approximately 2% of all sections) are currently at the highest level of exposure to flooding ('Extreme Exposure');
- Climate projections indicate that 179 sections will be classed as having 'Extreme Exposure' by the 2030s and, 568 sections by the 2050s; and

- The number of sections classified as having little or no exposure to flooding decreases dramatically over time.

3.1. Operating Company Incident Data Analysis

One of the key objectives of the project brief was to identify sections of the trunk road network that were particularly sensitive to surface water flooding. It was hoped that using a range of data sources, supplied by Transport Scotland and SEPA, we would be able to identify a shortlist of locations that would be suitable for a future more detailed investigation.

In addition to the data provided in Section 1, desk study work for this report also acquired the following data sources shown in Table 3-2.

Table 3-2 - Available Data

	Data	Stakeholder
1	Historical flooding information	Operating Companies
2	GIS layer of gradient of the trunk road	Transport Scotland
3	Flood Maps	SEPA
4	Climate Change Report	AECOM

The historical flooding records kept by Transport Scotland were limited and of varying quality, and as a result selecting locations based on this data alone was challenging. An alternative approach was a hotspot analysis, which could be undertaken due to the spatial nature of the data, to narrow down locations where flooding caused most disruption. The hotspot analysis excludes unsuitable locations based on other datasets provided as well as interrogating the historical flooding incident records. Details of the data sources used for analyses are described below.

Historical flooding data – Transport Scotland

Transport Scotland supplied Atkins with historical flood incident data in the form of an excel spreadsheet containing 1612 incident report details. All entries were recorded by the Transport Scotland appointed trunk road operators and later collated by Transport Scotland into spreadsheet format. The data was plotted in Geographic Information Systems (GIS) using coordinates supplied against each data record to enable identification of spatial trends that were not apparent from the data in its existing form.

Data was extracted based on key words, included in the descriptions associated with each incident record, that were considered to be relevant to trunk mains flooding in Scotland. Descriptions of the incident and corresponding mitigation was variable across the regions and were not consistent in reporting format. As such, a first pass selection of appropriate key words from the descriptions in the data had to be undertaken. The key words that were identified as being of particular importance were “Flooded”, “Flood”, “Blocked” “Closed”. Any records that had descriptions which were considered not to be of high significance (e.g. “Erected traffic light site”) or did not provide clarity on the type of incident were eliminated from the data that was plotted as ESRI shapefiles.

Spatial data was then analysed for clusters of incident records, to identify locations where recurring flooding had been reported. This was used to determine whether locations had potential to be used as sites for further investigation. The production of these additional layers also allowed us to identify the Operating Company responsible for recording each flooding incident. From this analysis we found a wider than expected variation in the recording of flooding incidents across each Operating Company, when length of trunk road, and weather patterns, were taken into account. It is unclear whether this variation in the number of incidents recorded relates to the Unit's approach to flood incident reporting, or whether the Units are affected by a disproportionate amount of flooding.

Road Gradient Data

Road gradient data was supplied by Transport Scotland in ESRI shapefile format which mapped the entire trunk road network in 10m lengths. Each of the 10m lengths was assigned the attribute of a percentage gradient accurate to 2 decimal places. The gradient network was split into separate layers so that locations with similar gradients were grouped together. The gradients recorded in the original data supplied ranged from -13.19% to 14.93 %.

As locations with steeper gradients would likely encourage runoff and not have issues with standing surface water, identification of potential hotspots was limited to areas with gradients of values between 0% and +/- 2%,. The resulting gradient layer was split into 16 individual layers ranging from -2% to +2% in 0.25% increments. These layers were compared with the filtered flooding incident data from Transport Scotland and locations that had high concentrations of incidents in corresponding reaches of low gradient, were identified and shortlisted as potential areas for further investigation.

SEPA Indicative Flood maps

Transport Scotland additionally supplied Atkins with SEPA's indicative flood maps in ESRI shapefile format, which outline locations that SEPA have identified as being at risk of flooding from surface water. The surface water flood outlines were cross referenced against the incident data and gradient data as detailed above. Having these maps also allowed the exclusion of locations that were recorded in the historical flooding incident data but fell within the fluvial and coastal flooding zones. The reason for excluding these locations was that the source of the flooding could not categorically be identified as originating from surface water, and there was not sufficient evidence from previous datasets that surface water flooding causes disruption in the trunk road.

Selecting Surface Water Flooding Hotspots

Several locations where all data sets overlapped were identified from the above spatial analysis, which gives an increased confidence that these areas have a high likelihood of being impacted by surface water flooding. Ten locations are listed in Table 3-3 below were selected as suitable areas for use as trial sites for surface water flood forecasting. These locations are detailed below and shown in Figure 3-3.

Table 3-3 - Flooding Hotspot Locations

Location	Route	Unit
Tarbet	A82	North West
Loch Leven	M90	North East
Fort William	A82 & A830	North West
Kintore	A96	North East
Greenock	A78	South West
Maybone	A77	South West
Glasgow Andersons	M8	South West
Bannockburn	M90	North East
Oxgangs	A720	South East
Keith-Huntly	A96	North East

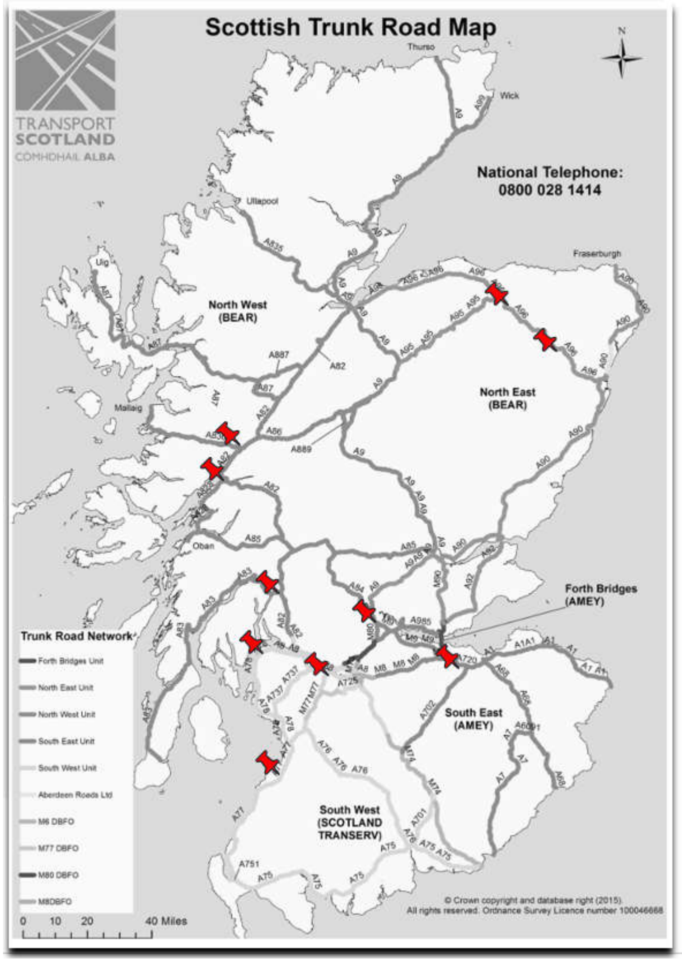


Figure 3-3 – Flooding Hotspot Map

3.2. Climate Change

In 2016 Transport Scotland commissioned AECOM to examine the potential impacts of climate change on the Trunk Road Network and identify how Transport Scotland and the supply chain should respond to these risks to become more resilient. The proposed outputs were as follows.

- A collated list of recommendations, actions and next steps;
- Briefing paper on key climate change threats to the trunk road network; and
- An inventory of most at risk assets, operations and interconnected services and infrastructure, based on location, recent events and future projections.

The identification of these sections of trunk network that are considered more vulnerable was envisioned to be for informing which parts of the network require the most attention, with regards to minimising future disruption and the cost associated with response and repair. It also aims to inform and facilitate the development of adaption plans and support future investment decisions.

AECOM assessed the current level of vulnerability of TS trunk road network assessed for flooding, landslides, high winds and snow and ice. This was done using an analysis of severe weather-related incidents over a 3-year period (2013-2016) as recorded in TS incident database. The study found that flooding was the type of disruptive severe-weather event that is most projected to affect significant parts of the Scottish trunk road network.

The future assessment has identified 76 sections of trunk road network that are at highest level of (Extreme Exposure) vulnerability to flooding. When climate change is applied - 179 sections have Extreme Exposure in

2030s and 568 sections have Extreme Exposure by 2050. Sections classed as having no to little exposure to flooding decreases over time (839 to 126 sections). Thirteen of these are mapped to reflect sections with the highest level of exposure to flooding (Figure 3-4), with the sections listed in Table 3-4. These are areas where intervention is likely to be required, to increase resilience to future flood events.

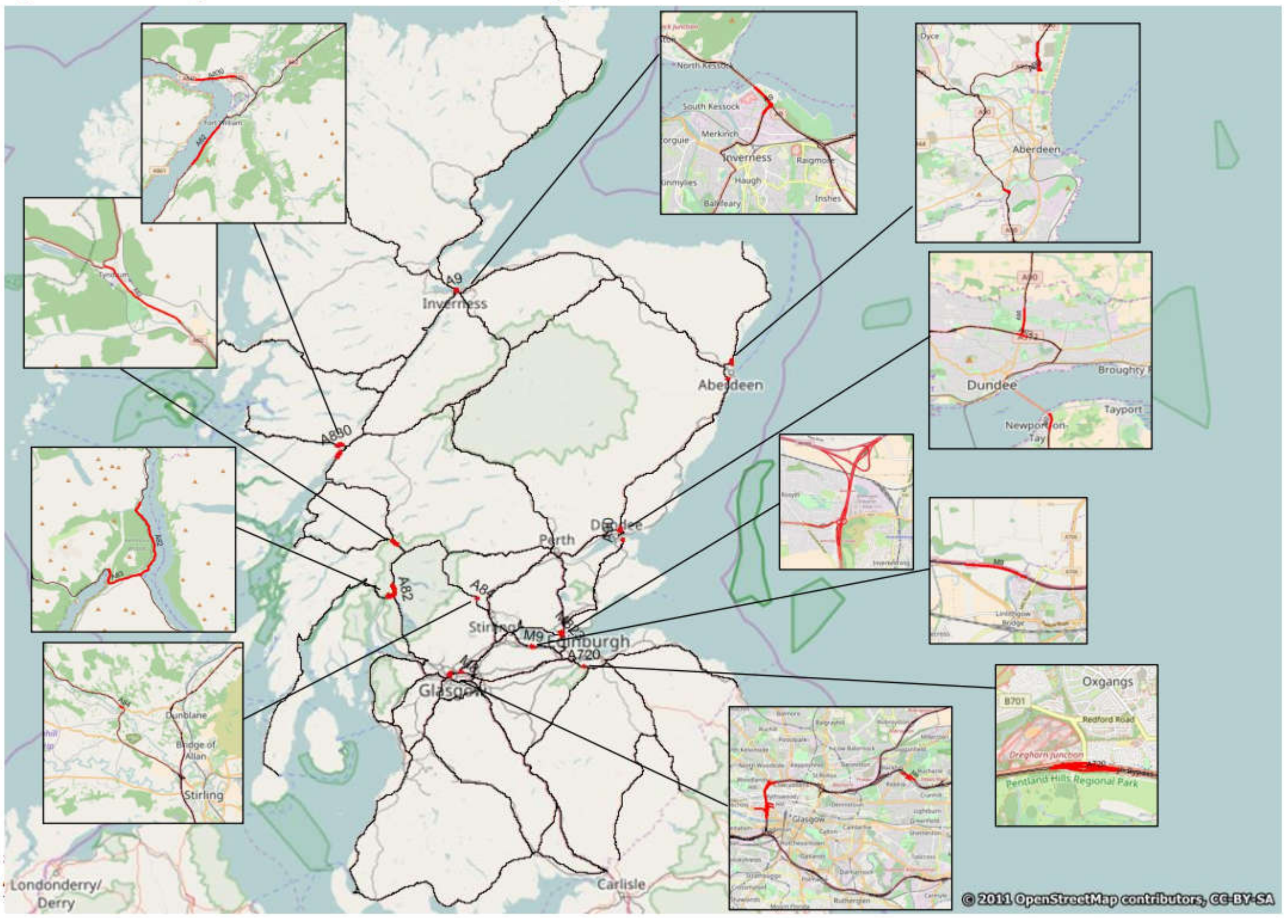


Figure 3-4 - Trunk Road with Highest Predicted Flooding Exposure

Table 3-4 - Trunk Road with Highest Predicted Flooding Exposure

	Location	Route	Unit
1	Fort William	A82 & A830	North West
2	Tyndrum	A82	North West
3	Tarbet	A82	North West
4	Stirling	A84	North West
5	Glasgow	M8	South West
6	Oxgangs	A720	South East
7	Linthingow Bridge	M9	South East
8	Queensferry Crossing	M9	FBOC
9	Dundee	A90	North East
10	Newport on Tay	A92	North East
11	Blackdog	A90	North East

12	Kirkton of Maryculter	A90	North East
13	Inverness	A9	North West

UK Climate Projections 18

UKCP18 climate projections were released by the Met Office in November 2018, as a major upgrade to the UKCP09 projection tools with updated observations and climate change projections to the year 2100 and globally. A summary of the UKCP18 findings for the UK in general are detailed below:

1. In general, the trend of warmer, wetter winters and hotter, drier summers continue to be predicted for the entirety of UK in UKCP18, which reflects previous projections in UKCP09;
2. Warming is projected to be greater in the summer than in winter, and to affect all areas of the UK;
3. Precipitation is anticipated to decrease significantly in the summer, and increase significantly in the winter – with more intense storms predicted during summer rainfall; and
4. Sea levels continue to rise, as projected in UKCP09, with the south of the UK expecting greater increases in sea level than the north.

Future analysis should be done to incorporate the numerical uplift projections from UKCP18, including better quality data that may be recorded/collected in future in terms of historical flooding. It is advised to use caution when utilising the results of the assessment due to the complex nature of climate change projections. Where possible, empirical evidence and local knowledge and expertise should be cross-referenced against the assessment to ensure reliability of the output.

SEPA Climate Change Guidance,

SEPA has taken account of the revised perception of climate change, including the new findings from UKCP18 within their “Climate Change allowances for Flood Risk Assessment in land use planning” document which was published in May 2019. The purpose of the document is to inform spatial strategy of development plans based on the best evidence available allowing Scotland to move towards delivering climate resilient places.

A key output of the guidance document is the revised uplifts to account for climate change. Some of the uplift figures suggested are as high as 56% for Argyll, Western Isles and the West Highlands (river flooding) and a rainfall uplift of 55% for the west of Scotland region when applied to pluvial flooding, which is a significant increase in design standards. Advice in the guidance will be applied to the trunk road design in line with the advice in the DMRB. The DMRB is currently being updated to reflect a number of changes in design standards. It is anticipated that it will state that latest guidance on climate ”Shall” be considered rather than “Must” this would in theory allow departures from the standard possible. However, in practice, it would be appropriate to use the new allowances in all situations.

4. Flood Forecasting

4.1. What is flood forecasting

Flood forecasting is generally defined as a method of estimating the magnitude, timing and duration of flooding in any given area. The main component of the forecast, as opposed to a flood warning is the “collection of real-time data for the prediction of flood severity, including time of onset and extent and magnitude of flooding” (Manual on Flood Forecasting and Warning, WMO, 2011). Whilst flood forecasting feeds into flood warning systems as part of wider flood risk reduction or flood management strategy, flood warning tends to focus on the interpretation, communication and advanced dissemination of information regarding the flood severity, expected impacts and actions around this to affected parties.

The WMO (2011) manual states that flood forecasting is a required part of flood management, as prevention and defence measures can never be completely effective due to the possibility of failure or exceedance in capacity of said defences. It also sets out the various elements that comprise a flood warning system. The key elements that need to be considered for good flood forecasting design are:

a) The hydromorphological characteristics of the basin, topography, geology and soils, and the degree of structural development;
b) The main physical processes occurring during hydrometeorological events; and
c) The type of service that is required and can be achieved technically and economically.

The minimum data required for a basic flood forecast include hydrological data/models, meteorological forecast or rainfall data and topographic data for the area under study. More complex studies may also require technical infrastructure, human resources and physical catchment data such as geology, soil and vegetation, as well as data on local sewerage systems that may interact with the hydrological catchment.

The complexity of a flood forecast is dependent on the drivers and characteristics of the location being assessed, as well as often being influenced by the governance and stakeholders involved in the management of river basins or drainage catchments in the area. The area of focus can range as large as cross-boundary locations where river basins cross local or national boundaries, flood risk assessments on a national scale down to small-scale local areas of known risk.

In addition to the above physical processes that influence the most appropriate modelling approach, consideration should be given to the type of communication and lead times required for the target population in the area for which forecasting is considered. The latter variables are specifically related to flood warning systems, rather than flood forecasting, however they are an important part of the picture in terms of reducing risk and appropriate hazard response. This is arguably the main driver for the establishment of flood forecast systems for many areas known to be prone to flood risk.

4.2. What are the benefits

The benefits of flood forecasting are the reduction of risk and damages to communities, property, life and economic activity from flooding. When communicated in a timely manner, flood forecasts enable authorities and the general public to prepare for flood events and the associated losses that may be caused by them. This can take the form of:

- Better management of assets;
- The establishing of flood defences, or ;
- Protection and loss reduction of property and life (in the form of evacuation and local short-term flood defence strategies).

4.3. What flood forecasting for surface water currently exists

Flood forecasting for surface water often takes the form of flood risk modelling and assessments, in areas with a high level of urbanisation or infrastructure which reduces natural permeable areas. Flooding in these areas often occurs when drainage systems are overwhelmed by intense rainfall, overwhelming sewer design capacities. In addition to the variables described in the section above surface water modelling often incorporates urban infrastructure such as buildings and roads to represent the overland flow that occurs when networks are overwhelmed and enables the identification of housing or road assets that may be affected by ponding of out-of-sewer flows.

The majority of the case studies examined as part of this study from the UK and the rest of the world appear to focus on surface water forecasting in highly urbanised areas, specifically city centre locations where traffic disruption would be significant in the event of road closure. In most cases the risk, and consequently impact of surface water flooding was assessed using flood models of varying detail often using design or observed rainfall events.

One of the studies focussed on the use of telemetry for early warning systems in known flood hotspots in 6 different countries, using a variety of different methodologies. Another case study assessed the efficiency of the UK Met Office Flood Forecasting Centre services, for Category 1 and 2 responders which was the only nation-wide study, which noted that surface water flood forecasting is particularly challenging due to the localised nature of such events. This was exemplified in the CREW pilot of a Grid to Grid (G2G) model in Glasgow where blending of rainfall inputs had to be undertaken prior to the modelling exercise to allow for differences in local variance. In addition to this the model had to be calibrated using good quality data and often with local knowledge as the model was underpredicting flooding in some known flooding hotspots in the East End of Glasgow.

4.3.1. UK & Rest of the world

A number of research papers related to the modelling of surface water flooding and its impact on transportation were examined as part of this study to understand current and past approaches in different parts of the world as well as in the UK. The summary of findings for these research papers are provided as part of Appendix C, whilst the conclusions are presented below in Table 4-1.

Table 4-1 - Summary of Case Studies from the UK and the Rest of the World

Location	Title	Author	Journal	Key Findings
Shanghai, China	“Evaluating the impact and risk of pluvial flash flood on intra-urban road network: A case study in the city center of Shanghai, China”	Jie Yin, Dapeng Yu, Zhane Yin, Min Liu and Qing He (2016)	Journal of Hydrology, 637, pp. 138-145	Study combines pluvial flood numerical modelling with a GIS based roads failure analysis. Design rainfall events used in 2D modelling with allowance for channelling of flows by roads, drainage capacity taken into consideration. Data requirements for this exercise were large, and reliable past flood data is required for calibration of the model for desired accuracy in the output. Roads failure analysis could be transposed to Scotland’s trunk road network if sufficient data and resources are available for pluvial

Location	Title	Author	Journal	Key Findings
				flooding, however would not be real time.
Dobrzykowice, Poland	"Pluvial Flood Risk Assessment Tool (PRFA) for Rainwater Management and Adaptation to Climate Change in Newly Urbanised Areas"	Sweranski, S., Chruscinski, J., Kazak, J., Swiader, M., Tokarczyk-Dorociak, K., and Zmuda, R. (2018)	Water, 10, 386, pp 1-20	This paper details the development of a flood risk assessment tool in ArcGIS, utilising a Python script to automate output from models within the ArcGIS environment. Risk scoring was undertaken based on intensity of rain in local areas in gridded rainfall inputs, level of property and potential damage to assets. Roads were seen to be at the highest risk of inundation at all levels of rainfall. Potential areas of flood that were not reported previously in the model, it is also hard to account for human measures that mitigate flooding which lead to lack of reporting. Size of model was small however still data and processor hungry and might not be suitable for area as wide as entire trunk road network in Scotland.
Multiple	"Real-Time Early Warning System Design for Pluvial Flash Floods – A Review"	Acosta-Coll, M., Ballester-Merelo, F., Martinez-Peiro, M. and De la Hoz-Franco, E. (2018)	Sensors, 2018, 18, 2255	Study examines and details early warning systems, with case studies of EWS implemented in areas with high risk of flash flooding in urban areas in multiple countries including Thailand, USA, Colombia, Philippines, Puerto Rico and Spain. Most case studies in this paper rely on telemetry or monitoring of on-ground conditions using sensors or weather radar in known hotspots, with an alert system enabled when set thresholds for the variables monitored (rainfall, reflectivity, water level or velocity) are exceeded. Methodology from this study could be transposed to known areas of flooding on the roads network in Scotland.
York, UK	"Beyond 'flood hotspots': Modelling emergency service accessibility during flooding in York, UK"	Coles, D., Yu, D., Wilby, R. L., Green, D., Herring, Z. (2017)	Journal of Hydrology, 546, pp. 419-436	This paper took a roads network approach similar to Shanghai study, with a pluvial and fluvial flood model linked to an "accessibility model" for first responders in the city of York in the form of ambulance and fire and rescue service. GIS was used for network analysis, which was overlain with areas that were predicted to have >25cm and >100m^2 of flooding, taking into account statutory 8- and 10- minute target response times for high priority, life threatening incidents. Historical

Location	Title	Author	Journal	Key Findings
				events were used for this analysis. Modelled surface water flooding had a larger spatial spread than fluvial flood event analysed. Conclusions add that performance of model had to be calibrated against reports and pictures of flooding that were not flooded in the model, like in previous studies. Further to this, when historical traffic flow data was recommended as an additional source of data to increase accuracy as normal traffic flow assumptions may underestimate response times during flood events.
UK (Various)	“Surface water flood warnings in England: overview, assessment and recommendations based on survey responses and workshops”	Ochoa-Rodriguez, S., Wang, L.P., Thraves, L., Johnston, A. and Onof, C. (2018)	Journal of Flood Risk Management, 11, S211-S221	This paper details the progress made in surface water flood forecasting since severe flood events in the UK in 2007, caused primarily by surface water flooding. The purpose of the study was to establish the usefulness of FFC services by the Met Office and EA that relay extreme rainfall alerts to Category 1 and Category 2 responders and Surface Water Flood Risk Assessment which is a tool that gives a risk weighted score at country and local authority level, issued daily to recipients with a 5-day lead time. The main finding of this was that although recipients found some level of usefulness in the alerts provided, many found that the nationwide nature of these forecasts were too broad and did not enable more accuracy in timing and location considering the localised nature of surface water flooding. Probability of likelihood and impact was also considered to be insufficiently emphasised leading to frustration due to “over-reaction” in responders. Local data and a more targeted approach was favoured by almost all respondents and workshop attendees interviewed during the study.

4.4. The CREW Study

This study was conducted by a consortium of research providers from the Centre for Ecology and Hydrology, The James Hutton Institute, the Met Office and SEPA for CREW to expand SEPA’s surface water forecasting capabilities at the time. The aim of the study was to establish an appropriate forecasting and warning system for surface water flooding in urban areas, which was then subsequently piloted at the 2014 Commonwealth Games in Glasgow.

The methodology of the approach chosen specifically used nationally available datasets and developed an operational surface water flood risk forecast with a 24-hour lead time for a 10km by 10km area in Glasgow's East End. The process was split into 3 stages:

1. Creation of an appropriate rainfall prediction model;
2. Development of an appropriate surface water flood model; and
3. Development of an impact assessment to create a forecast impact library for an operational model

The pilot operated from June to August 2014 over a 10km by 10km area over the East End of Glasgow, in an area previously affected by major flooding in July 2002. It provided strategic flood guidance to the Games organisers and emergency responders in real-time, throughout the Games.
Using state of the art weather and hydrological models, the forecasting system integrated the real time intensity and pattern of rainfall forecast over a 24h period with detailed information on land use and risk of flooding to properties and transport links.
The project assessed how this approach could be integrated into SEPA's existing flood forecasting mechanisms to deliver real-time information on the severity of surface water flooding impacts in urban areas.

4.4.1. Research on Existing Forecasting Methods

Intensive Rainfall Forecasting

As part of the research for the study current approaches for intensive rainfall and surface water flooding and developments in this field were reviewed. High resolution intensive rainfall inundation models were already existing at the time, and heavily used for surface water flooding design applications. However, these are not appropriate for real time forecasting. At the point of research, the existing method of surface water forecasting in real time was found to be a combination of rainfall threshold exceedance and use of flood planning maps. Beyond 6 hours ahead, Numerical Weather Prediction (NWP) provided the most accurate forecast of rainfall. In addition to this, a UK Variable (UKV) grid precipitation model was available from the Met Office at a 1.5km grid. This used together with NWP was found to be skilful at predicting maximum rainfall accumulations, but timing and location can be high uncertain (1hr and 25km respectively).

For very short lead times, Short Term Ensemble Prediction System (STEPS) nowcast provides useful radar-rainfall extrapolation ensemble forecasts, blended with the deterministic UKV model up to 6 hours ahead. In addition to this, MOGREPS-UK 12km grid ensemble was available for Scotland (SEPA) to conserve data volumes but UK wide MOGREPS-UK updated in 2012 to provide 2.2km grid resolution, with better results than previous MOGREPS-R system (12km grid).

The main problem encountered in all the rainfall data was related to accuracy of modelling, where verification and calibration are dependent on good quality rainfall observations from telemetry. In Scotland in particular, significant areas are under-observed due to;
a) a lack of real-time reporting rain gauge networks;
b) distance from weather radar with factors present influencing radar's ability to estimate ground level rainfall; and
c) Remote and mountainous terrain in some parts of the country.

At the time, improvements to rainfall observation across Scotland was being made by work in progress to use real time polling of SEPA's tipping bucket rain gauge network and to complete the UK radar network update. This would enable better rainfall predictive capability in real time in Scotland at the completion of this improvement works.

The study noted that further work was required to optimise the use of the new radar technology, particularly its dual-polarisation capability, and to combine rain gauge and radar observations more effectively. To date it is not known if this work has taken place.

A blended precipitation ensemble forecast was further introduced in October 2013, combining:

- 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; and

- Hourly precipitation forecast using an enhanced data assimilation method implemented at the Met Office in 2015/6.

However, this data is also highlighted to have a spatial uncertainty of more than 10km which can be problematic for accurate surface water flood forecasting given the localised nature of this type of flooding in particular.

Urban Surface Water Flood Forecasting

As with the worldwide research, this study notes that real time surface water flood forecasting model run times need to be short to allow production of longer lead-time ensemble forecasts required to facilitate effective mitigation actions. Current approaches of modelling both surface runoff and underground sewerage network are detailed and demand long run times, making them unfeasible for this purpose.

In order to work around this, an estimate of sewer capacity is ideally used. Even with the use of sewer capacity estimates, 2D modelling of surface water currently still fails to meet real-time forecast run-time requirements. Moreover, the investment required, both in computing facility as well as time inputs from qualified personnel to support a real time model with appropriate verification is substantial. This is particularly the case when considering the continuous running of a model and model maintenance across all time-steps for model states.

As such it was concluded that current inundation models implemented for design and planning are not well suited for real-time application and require development and restructuring of the software. In the majority of cases inputs to these models relate to an effective rainfall design storm profile and do not include an explicit space-time representation of runoff production and water loss accounting. Flood Modeller (previously ISIS)-FAST was considered by the study to be the most suitable of these models for surface water inundation in terms of model run time, however it was also stated to require significant further development, testing and verification for use as an operational tool.

Surface Water Flood Forecasts

Real time surface runoff forecasts can be provided by CEH's Grid to Grid (G2G) distributed hydrological model. G2G is used currently real-time across Scotland for fluvial flooding by Scottish Flood Forecasting Service. Surface runoff in the model is routed through the river network to get fluvial flood forecasts and is available to be configured as an output to enable forecasting of surface water flooding.

Most existing approaches for real time surface water flooding warnings are based on rainfall threshold exceedance methods and identify risk areas in map form. G2G models can provide further accuracy on this type of approach by taking into account factors such as surface cover, soil properties and antecedent moisture conditions.

Other existing, more local approaches examined by the study include a more detailed hydraulic model JFlow+ that was being used primarily for the Glasgow Pluvial Flood Mapping project. The outcome of this modelling is detailed datasets on pluvial flooding associated with a suite of design storms of varying severity. The goal of the project was to link the offline flooding datasets with G2G methodology to enable better resolution in real time G2G surface water forecasts. Further to this, CEH and SEPA were also working on combining the G2G flooding hazard footprints with impact datasets. This data was pulled through to the CREW project to provide strategic surface water hazard impact maps for the Commonwealth Games scenario.

4.4.2. Pilot Study – Commonwealth Games

The aim of the pilot study was to ensure key responders in Glasgow inclusive of the City Council, Transport Scotland, Scottish Water, the Scottish Government and the Commonwealth Games organisers were able to react and mitigate effects of surface water flooding during the Commonwealth Games event. SEPA organised a steering group made up of these organisations detailed the needs of these parties from a forecasting and corresponding alert system. These were detailed as being:

- A 6 to 24-hour lead time for the forecast to ensure sufficient time for preparations;
- Guidance on flood event locations, timings, possible impacts and severity; and
- Stand-down messages when events were over, or a risk-level reduced

To address these needs a G2G model approach was considered the most appropriate in terms of lead times requested for by the steering group. A location in Glasgow's East End, with an approximate area of 10km by 10km grid was selected for the pilot study, with rainfall inputs from an ensemble STEPS nowcast system and a blended MOGREPS-UK precipitation ensemble forecast, at a grid of 2km for the STEPS radar data and 2.2km for the MOGREPS-UK forecast. These were provided by the Met Office to SEPA at a 2km resolution, for 15-minute rainfall accumulations on a 22km by 22km domain over Glasgow, 4 times daily. In addition to this, observed gridded rainfall based on telemetry rain gauges within the vicinity of the Glasgow pilot study area were used as input to the model in the period between the daily G2G Scotland states and the start of a G2G Glasgow forecast.

The G2G model approach is already used by FEWS Scotland as well as in England and Wales to provide fluvial flood forecasts, however it can also generate surface water outputs. These are represented by a soil, slope-controlled, probability-distributed, storage-capacity and scheme subject to land-cover (e.g. urban) effects. G2G runoff production is shaped by storm pattern and spatial datasets on known landscape properties, as well as continuous water accounting (changing antecedent soil moisture). The outputs from G2G models are gridded surface runoff estimates.

As this type of modelling doesn't provide impact assessments, offline inundation maps were used to supplement the G2G model in the form of SEPA's pluvial flood hazard maps. A 1km grid-cell impact definition map was developed specifically for the Glasgow pilot study by SEPA to assess disruption to 6 different receptor types:

1. Population (number of properties affected by 1km pixel);
2. Community Services;
3. Utilities;
4. Commercial Properties;
5. Railway; and
6. Roads.

The potential impacts in this grid were combined with likelihood to assign an overall risk level. The impacts were grouped into people and property impacts (first 4 receptors) and transport impacts (railway and roads), with transport being a separate category due to the interconnected nature of transport networks leading to disruption in wider areas than just the cell where impact is greatest. Minimum effective rainfall thresholds were established for each group of receptors and severity levels then compared against real-time forecast surface runoff as estimated in the G2G model.

Manual checking and supplementation with local knowledge of flooding in the study area was necessary to verify the 1km grid cell impact definitions. A site visit was conducted by a local expert from Scottish Water to identify particular hotspots for surface water flooding. For example, London Road in the East End of Glasgow as determined to be a high risk area even at low rainfall totals, however was mapped only to be at risk at a 200 year plus climate change uplift scenario, highlighting the importance of local stakeholder knowledge in flood mapping. The study also recommends new urban areas undertake manual checking as well for impact assessments to enable better accuracy.

Further to this, probabilistic outputs from the model were produced in gridded format (rainfall, surface runoff, transport impacts, people and property), supplemented with surface runoff time-series per grid cell for each time-step of the whole forecast. These referenced the probability of exceedance of set thresholds for each receptor in the gridded formats and of surface runoff accumulation exceeding 13.5mm to 16mm in 3 hours at any time within the whole forecast, and 6 hour forecast windows for the time-series format.

The overall process is visualised in Figure 4-1 below:

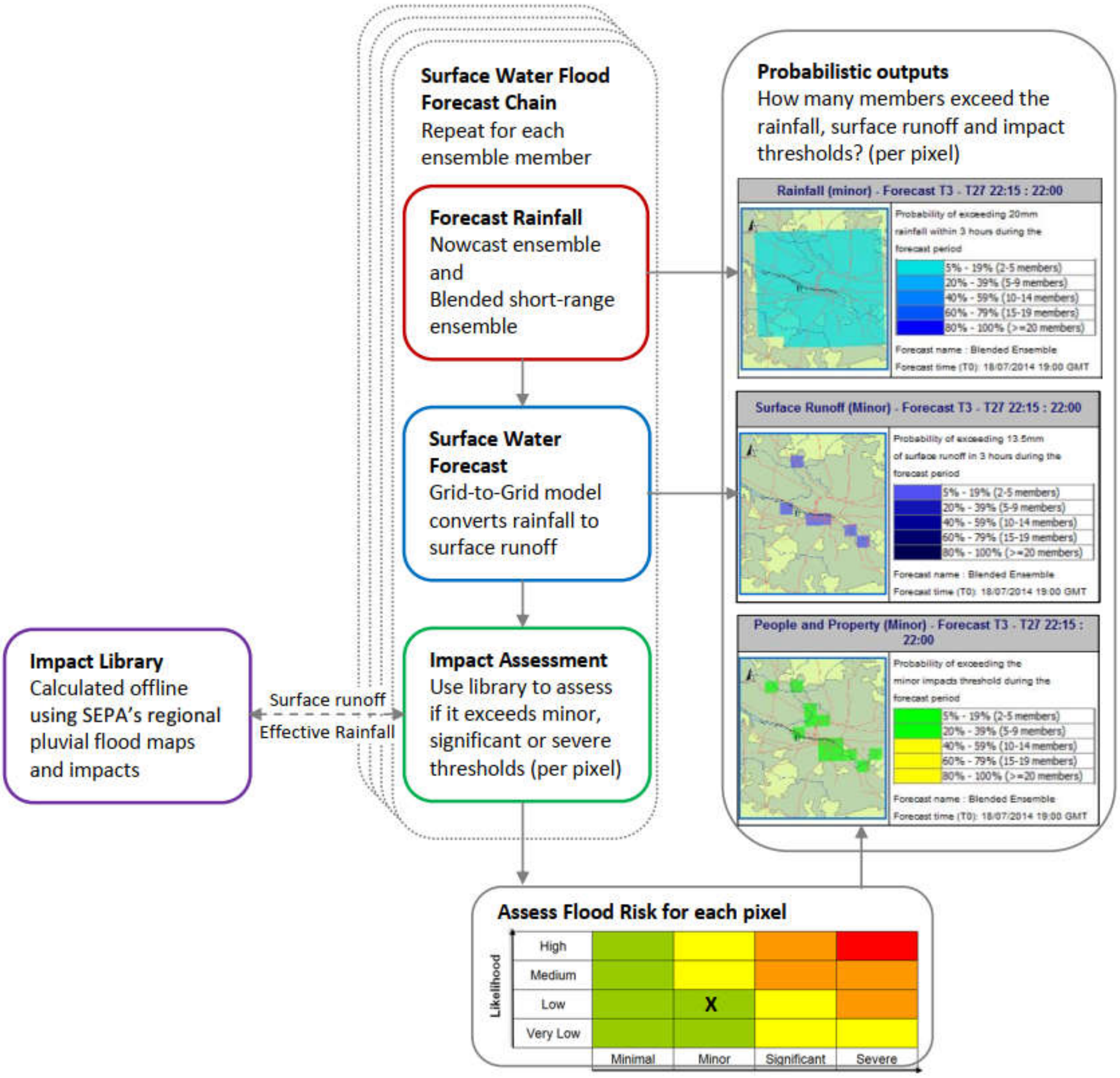


Figure 4-1 - Overview of the forecasting process and examples of probabilistic outputs produced for pilot study (CREW, 2015)

Communication of Outputs

The model outputs were produced as web reports within the FEWS Glasgow system (Flood Early Warning System) developed by Deltares, a SEPA supplier who provides the platform for the FEWS Scotland system. Due to the small study area for Glasgow (22km by 22km) the processing time for outputs was approximately 2.5 minutes. Outputs were issued every day at 1700 to responders based on the blended ensemble forecasts at 1300 from the Met Office. This report evaluates the FEWS Glasgow output on the following elements:

1. A Surface Water Flood Risk Summary (based on Flood Risk Matrix) for next 24 hours;

2. A weather summary;
3. Detailed assessment of the surface water flood risk;
4. Information on the start and end-time of heightened risk; and
5. Additionally, list of possible impacts where this was relevant.

A briefing note was provided to accompany these outputs, with key points on the forecast, forecast interpretation guidance, possible magnitude of impacts, uncertainty in the outputs and timings. The briefing note also gave some context to the forecast through comparison with previous events and information on when further updates were to be provided. Verbal briefing was also provided by the Scottish Flood Forecasting Service providers to SEPA Resilience Officers working during the Games.

The communication of this was found to be useful for 3 events during the Games, with briefing notes found to be the most useful output by responders. Due to the evolving confidence and risk levels through the day, communication of risk was challenging for the output providers. Nonetheless forecast outputs for the two events over the Games were found to be in reasonable agreement with anecdotal impact reports in terms of transport disruption and road conditions despite some uncertainty in timing and location of the heaviest rainfall in the third event.

Recommendations and Future Development

Further to the pilot study, feedback was collated from SEPA and other members of the Steering Group and some recommendations made as to ways to transfer the methodology of the Glasgow pilot study to other parts of Scotland.

The first recommendation highlighted is the need to revisit the current operational set-up of how FEWS Glasgow interfaces with the general FEWS Scotland forecast. The outputs for multiple urban areas would also require some thought, as there is the option to have a replica of the FEWS Glasgow system for each urban area selected though there is uncertainty as to whether this this the best approach for a nation or region-wide level, such as for the entire trunk roads network in Scotland.

In terms of receptors applying this to a trunk road network would be more simplistic, however the study notes that the resource investment due to the real-time nature of the forecasting was high due to the need for expert interpretation and forward communication of results to responders. If automation is considered in a first-pass assessment of risk level on a region, area or city this might produce efficiencies in human input for future forecasts in other applications of this type of system.

Along with high resource investment other potential limitations were also identified, with increasing coverage area or increases in forecasts in terms of length, frequency or number of rainfall ensembles requiring additional computing resources than used by SEPA in the course of this study. The requirement for any future forecasts needs to be assessed prior to undertaking forecast work elsewhere to ensure sufficient resources for seamless model runs and outputs.

The success of the Glasgow Pilot was also attributed to input from end-users and the Steering Group involved in the study. As such, any future forecasting also required good stakeholder engagement and management of their expectations. As previously mentioned, resource commitment and overheads for the Glasgow Daily Surface Water Flood Forecast was high, and due of the level of service offered and the high-profile nature of the games. For a more “day to day” operational model, level of service might need to be reassessed to ensure that this can be balanced with available resource. The study also highlighted that the involvement of multiple organisations can present challenges in aligning contributions

Finally, communication to the public was not a part of this study, however if considered in other flood early warning systems, the method of communication needs to be carefully considered whilst also taking into account existing flood warning services such as the Flood Guidance Statements, Flood Alerts and National Severe Weather Warning Service Alerts which are available nationally. Following the completion of the CREW project SEPA, and Transport Scotland submitted a bid to NERC for funding to develop that capability for the trunk road network but was unsuccessful at the last hurdle. Research would focus on:

- Engagement with customers/partners and possibly the public about their needs (spatial scale, lead time, content/format of surface water flooding alerting, perception of risk and uncertainty etc…),including Transport Scotland, Local authorities, Scottish Water, BGS;
- Review of science and technologies and future Met Office data and international practise and review of technical options (things would have moved on since FEWS Glasgow); and
- Staged development/trialling of system and service.

5. Requirements of a flood forecasting system

5.1. Operational Requirements from TS

The main considerations for Transport Scotland to take into account to establish a future flood forecasting system are:

1. Purpose and Forward Communication;
2. Level of Detail/Forecasting Approach; and
3. Data Requirements and Quality.

Forecasting Purpose and Forward Communication

It is important to first and foremost establish the purpose and the intended target group of the flood forecast system, as this determines the level of detail expected of the forecast and the method of onward communication to this group. As seen in case studies examined above, the method of onward communication can be very important for large groups such as general members of the public, and clarity of the message of where and when flooding is forecast to happen is important to ensure that sufficient time is given for response or limitation of damages from predicted flooding.

The target group can also determine the appropriate lead time for a flood forecast. For roads users the vehicle class may limit diversion options in a flood event, specifically for larger vehicle classes which might not be able to access certain routes where weak bridges, tight junctions or lack of height clearance around structures in rural areas may exist. If diversion or road closure from flooding is expected, a longer lead time may be required for roads users in these vehicle classes for traffic routing to be planned in advance. Similarly, for response times for Operating Companies on the trunk road network, longer lead time would enable them to ready and mobilise resources especially in areas where capacity or structural issues are known to cause problems regardless of a lack of operational issues in the road drainage system.

The intended target group can also influence the level of coordination and investment in infrastructure for communication. Some examples of types of onward communication are:

1. Direct communication to user (e.g. email to Operating Companies);
2. Push-notifications to subscribers for flood forecast warnings;
3. Automated social media updates (Facebook, Twitter etc.);
4. Online real time mapping portal reflecting road condition;
5. Intelligent Transport Systems with real time warning; and
6. Traditional media outlets (radio, television and newspaper)

Level of Detail

The second thing that Transport Scotland may want to consider is the area of coverage of their flood forecasting system. As detailed in previous sections, the minimum requirements for a flood forecasting model are topography data, rainfall data and the physical catchment characteristics. For the prediction of surface water flood forecasting it is also important to understand the interaction of the road drainage system with rivers and or the coast in the area concerned.

For this reason, it is anticipated that a detailed model of the entirety of the trunk road network in Scotland would be data and processor intensive and would also require regular maintenance to reflect any changes in ground conditions. This approach would also require initial calibration from observed data from either historical known flood events to ensure accuracy in forecast. This last consideration is particularly important if the main purpose of the flood forecasting system is to ensure that Operating Companies have adequate lead time and resources to respond to a predicted event.

A more targeted approach of trigger flood forecasting method focussed at known flood locations from historical incident reports could be used to avoid the data and hardware requirements of a continuous model of surface conditions. This would require some “front-end” modelling to determine the trigger rainfall event that overwhelms the capacity of the network and for flood warnings to be disseminated when such a rainfall event is predicted to occur by the Met Office in that location. It can also rely on telemetry data for rainfall data, from level/flow gauges in the drainage system, tipping bucket rain gauges installed in known flood risk locations or from pressure or level sensors installed in the network. An existing CCTV network may also be used to determine road surface conditions using machine learning. Whilst this approach takes some front-end investment in terms of material to enable recognition of reflectiveness on road surfaces once this is set up it can be effectively autonomous and require little human input except for some checking in the event of a flood warning being raised.

It would also be prudent to include locations assessed to be the most vulnerable to flooding in the future from predicted precipitation increases from UKCP18 in this method. For this, a second exercise of assessing vulnerability should take place as described by the AECOM study, using the UKCP18 and any updated SEPA flood maps for assessment to bring the previous vulnerability assessments up to date.

Data Requirements and Quality

Imperative for the accuracy of a flood forecast system is the data that is required to input into the model. Depending on the approach, data for rainfall would need to be acquired from the Met Office, topographical/surface elevation data for an understanding of low points where pooling may occur during heavy or long duration rainfall, some detail about the drainage system capacity as well as empirical data on known areas of flooding, and data around those flood events for verification.

The latter of these data sources is one that was found to be important in at least two of the case studies examined in section 3.4 above, and in the CREW case study to be of great importance to not only determine model accuracy in flood modelling for surface water – but also to determine areas of priority especially for real time systems for ground conditions where flash flooding from surface water can occur very quickly, and which may not be easily determined from data that covers larger areas such as radar rainfall. For this to occur, good quality data that is consistent across all regions in Scotland needs to be acquired from road operating companies to enable calibration and focussing of resources to understand the scale of the problem before investing any resources in modelling activity.

Scotland-wide LiDAR or elevation models do not currently exist, so some cost might be required for the procurement of elevation data for the purposes of numerical pluvial flood modelling. Depending on the desired accuracy of forecasts, the resolution of this data is also important. Vertical accuracy may be further decreased by any spatial interpolation between known road surface elevations and the surrounding environment which is important in situations where road surface water flooding is influenced from hillslope runoff or field runoff during intense rainfall events. It should also be noted that structural features that already exist such as flood defences where relevant might not be adequately captured in models that use a coarser mesh. As such this element of the data can be a costly investment if full road surface runoff modelling is desired for forecasting purposes.

The road drainage system may also be influenced or overwhelmed in specific locations by interactions with river systems, which would need to be accounted for in any modelling where the delineation between surface water and fluvial flooding is not as clear cut.

For more in-depth models further data such as soil moisture, soil type, sewerage capacity from urban areas adjacent to trunk roads, and evaporation rates would be required, or would need to be assumed to get the most accurate output for forecasts possible.

5.2. Operational Requirements from the Road Maintenance Operators

As detailed earlier in sections 2.1 and 4.1, some data for historical incidents on the road network was provided by the Road Maintenance Operating Companies (Amey, BEAR Scotland and Scotland Transerv). The data provided was over a period of 2 years. The dataset provided good detail in terms of date of these incidents and location of incident, however the details of each event recorded in “Comments” was variable depending on the company that submitted the data. These did not always include sufficient information for a third party to assess the cause of the event and what mitigation was taken after the event when flood waters had receded.

Following all of the above, and to develop a deeper understanding of how OCs and DBFOs operate in practice in relation to flooding incidents it would be useful to conduct a stakeholder questionnaire survey. A suggested example for such a survey is included in Appendix B. In this the questions are grouped as follows:

- Current Flood Risk Management, focussing on frequency and standard operating procedure in response to flooding on the road network in terms of flood response plans, prioritisation of response, communication to other parties and investigation of flood causes.
- Flood Forecasting. designed to understand the need for a flood forecast system by OCs, and what the required set up for this should be to be of use to maintenance and management crews from the OCs. The full questionnaire is provided in Appendix B to be disseminated to OCs by Transport Scotland.

5.3. Summary

Given the large spatial coverage of Scottish trunk roads any flood forecasting activity to be undertaken on the entirety of the network would require a significant amount of data input. Technical infrastructure and the right staff resources for interpretation and dissemination of the results would also be a key consideration of an appropriate early warning system for Transport Scotland.

Implementation and operational costs vary widely based on the type and level of accuracy of data required, the flood forecast approach (real time vs pre-simulated scenarios) and the type of alert system of choice. As such, high level decisions on the purpose and the audience of a flood forecasting system and an associated early warning system are necessary to understand the level of investment required.

Further to this, data quality is an important factor in determining forecast accuracy which often requires investment prior to any modelling activity. In the case of Transport Scotland, better data could be collected on the side of incident reporting which would greatly improve calibration of any models that may be required to forecast surface water flooding.

From the discussion and analysis in the previous sections it is clear Transport Scotland has the outline of a FREW and an operational need to improve this it inform decision making across the key areas of Flood Risk Management (avoid, warn and inform, and adapt and defend, as shown in Figure 5-1 below).

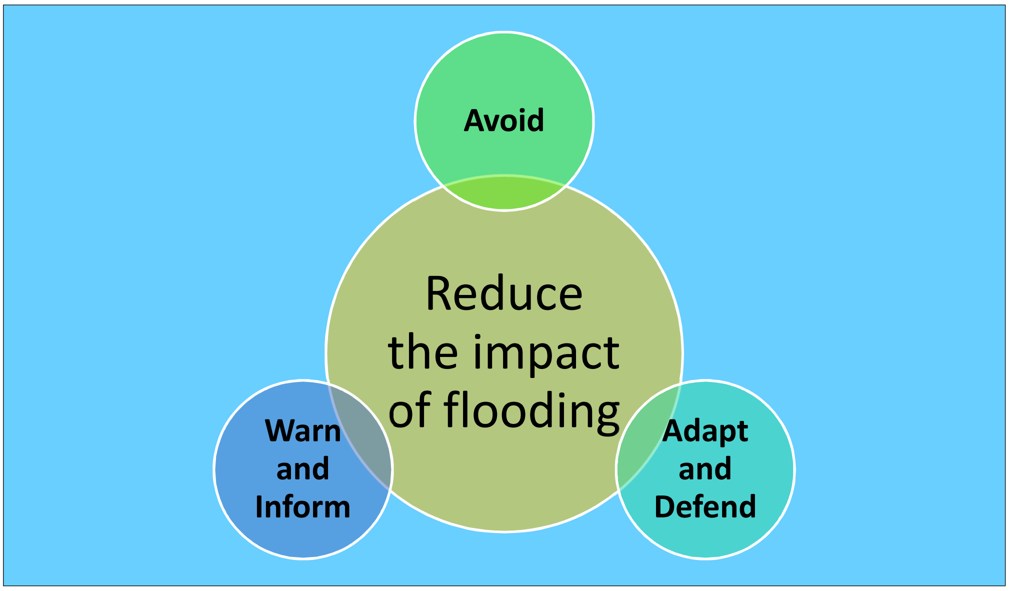


Figure 5-1 - Key Areas of Flood Risk Management

Recommended actions to define and establish a Transport Scotland FREWS are show in Table 5-1 below

Table 5-1 - Recommended Action to Define and Establish a Transport Scotland FREWS.

#	Action	Details
1	Develop a position paper on the scope and first principles for a Transport Scotland FREWS.	Given the data-intensive nature of surface water flood forecasting it is necessary to first make some decisions on the following before defining the system. • The level of investment and resources required. • What can be achieved with existing funding and resources. Define the intended recipients, and method of communication for flood warnings.

#	Action	Details
2	Assess the known locations of regular structural failure, operational issues, and capacity issues.	The complexity of the CREW approach to surface water modelling makes this type of modelling difficult to scale to the entirety of the Scottish trunk road network without significant cost implications. Understanding where current problems are from the companies that manage, and often mitigate flooding on trunk road networks would enable the identification of locations that suffer from flash flooding from overwhelmed capacity.
3	Evaluate key areas where flooding has caused safety issues on the network	Reaching out to organisations such as Police Scotland to identify key areas where flooding has caused safety issues on the network would support the FREWS approach. This will also help understand if there are any trends in flooding where addressing any key issues or mitigating flooding might be crucial.
4	Determine the purpose and objectives of a FREWS forecasting system	For example, the forecasting system might enable better asset management through the identification of areas where capacity is regularly overwhelmed due to old design, or where structural or operational failure often occurs to determine where investment might be made in the road drainage system to increase capacity and operation for the future, taking into account climate change. As determining the cause of flooding on the motorway can sometimes be problematic during the flood event, better records of each flood incidents are required

#	Action	Details
5	Develop best practice or specification for data collection on the incident reports.	It is recommended that a best practice or specification for data collection on the incident reports given by operating companies is created and issued to enable better record keeping. This should specify the main required elements of an incident report. This can include the following • How flooding was reported to the OC; • Whether the flooding was due to operational, structural or capacity problems; • Mitigation taken at flood location; and • Whether full or partial road closure was required. Pictures of the flood incident, and or of drainage system where problems were encountered
6	Implement a real time telemetry approach for each location detailed in the Early Warning Systems research paper.	Collection of the above data and investment in procuring further data might require some time for adequate calibration of a flood forecasting model, so it is recommended that this is supplemented in key problem areas with telemetry where data can be collected “real time” with set thresholds for each location as detailed in the Early Warning Systems research paper. This would allow for priority areas where flooding is most disruptive to have a preliminary warning system before large, detailed models can be built and calibrated for accurate forecasts.

6. Next stages

6.1. Approach to flood forecasting surface water

Given the data-intensive nature of surface water flood forecasting it is necessary to first make some decisions as to the level of investment that is desired for a flood forecasting system, to understand what can be realistically achieved with available funding and resources at Transport Scotland. The intended recipients of flood warnings would also need to be predetermined as communication to relevant parties can also constitute a significant investment in existing communications infrastructure.

The complexity of the CREW approach to surface water modelling makes this type of modelling difficult to scale to the entirety of the Scottish trunk road network without significant cost implications. As such it might be advisable to first undertake an assessment together with Operating Companies of known locations of regular structural failure, operational issues and capacity issues. Understanding where current problems are from the companies that manage, and often mitigate flooding on trunk road networks would enable the identification of locations that suffer from flash flooding from overwhelmed capacity.

More importantly, it might also be necessary to reach out to Police Scotland to identify key areas where flooding has caused safety issues on the network to understand if there are any trends in flooding where addressing any key issues or mitigating flooding might be crucial.

Transport Scotland might also consider what the purpose of the forecasting system is. For example, the forecasting system might enable better asset management through the identification of areas where capacity is regularly overwhelmed due to old design, or where structural or operational failure often occurs to determine where investment might be made in the road drainage system to increase capacity and operation for the future, taking into account climate change. As determining the cause of flooding on the motorway can sometimes be problematic during the flood event, better records of each flood incidents are required.

It is therefore recommended that a best practice or specification for data collection on the incident reports given by operating companies is created and issued to enable better record keeping. This should specify the main required elements of an incident report. This can include:

1. How flooding was reported to the OC;
2. Whether the flooding was due to operational, structural or capacity problems;
3. Mitigation taken at flood location;
4. Whether full or partial road closure was required; and
5. Pictures of the flood incident, and or of drainage system where problems were encountered.

Collection of this data and investment in procuring data might require some time for adequate calibration of a flood forecasting model, so it is recommended that this is supplemented in key problem areas with telemetry where data can be collected "real time" with set thresholds for each location as detailed in the Early Warning Systems research paper. This would allow for priority areas where flooding is most disruptive to have a preliminary warning system before large, detailed models can be built and calibrated for accurate forecasts.

Our discussions with Transport Scotland have determined a series of branches who have an interest or involvement in developing an FEWS. These are as follows.

- The Intelligent Transport Systems branch, who lead on the delivery of the Future Intelligent Transport Systems Strategy - 2017 which outlines three key needs as follows.

- To ensure it has a distinctly Scottish context, aligned with the Scottish government's purpose, national priorities and reflecting the diverse nature of the strategic road network and the geographic and socio-economic landscape of the country.
- To ensure it is customer-focused and investments contribute to a safe and efficient road network and are informed and driven by user needs.
- To ensure that decisions on investments in future ITS provision and operation align with TS's established investment hierarchy and are objective-led.

- The four specific objectives for the strategy are as follows.
  - Innovation and Horizon Scanning.
  - Customer Focus.
  - Planning and Adaptability.
  - Asset Management and Delivery.
- The Transport Resilience branch, who lead on the resilience approach described in the Road Asset Management Plan for Scottish Trunk Roads – 2016, including the development of the DRAT tools, and the shaping of the of the flood risk management plans.
- The Environment and Sustainability branch who are leading on the delivery of Transport Scotland responsibilities under the Flood Risk Management (Scotland) Act 2009
- The Asset Management branch who are currently updating the Operating company Contracts (NMC) and the Asset Performance Management System (APMS)

The successful delivery of a Transport Scotland FREW will depend on the coordination, management, and collaborative approach of the work of the above branches, together with the support of key stakeholders,

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Appendices

Appendix A.

A.1. Table of Incidents Recorded per Trunk Road (Scotland)

Trunk Road		Region	Number of Incident	Met Office Named Incident	Flooding/Flooded
A1	Edinburgh – Berwick Upon Tweed	South East	12	0	1
A68	Edinburgh – Carter Bar	South East	12	0	5
A6091	Melrose	South East	0	0	0
A7	Galashiels-Carlisle	South East	6	2	2
M73	Maryville – Mollinsburn	South West	0	0	0
M74	Glasgow – Carlisle	South West	41	6	6
A75	Gretna – Dumfries – Stranraer	South West	34	2	4
A76	Dumfries – Kilmarnock	South West	22	2	3
M77/A77	Glasgow – Stranraer	South West	71	4	7
A78	Greenock – Prestwick	South West	48	8	6
A701	Dumfries – Beattock	South West	14	8	0
A702	Edinburgh – Abington	South East	11	8	4
A720	Edinburgh City Bypass	South East	7	4	0
A725/A726	Shawhead – East Kilbride – Phillipshill Roundabout	South West	7	2	0
A737/A738	St James Interchange – Kilwinning – Hawkhill	South West	21	2	2
A751	Inchparks – Invermessan	South West	0	0	0
M8/A8	Edinburgh – Greenock	South West	165	16	15
M80	Glasgow – Stirling	South East	4	0	0

A82	Dallnottar – Inverness	South West	141	30	43
A83	Tarbet – Lochgilphead	North West	112	16	32
A84/A85	Stirling – Crianlarich	North West	178	32	49
A85	Tyndrum Oban Road	North West			
A85	Perth – Lochearnhead	North West			
A85	Barnhill Interchange	North West			
A86	Spean Bridge – Kingussie	North West	24	2	10
A87	Invergarry – Kyle of Lochalsh – Borve- Uig	North West	20	0	5
A823	Pitreavie Spur	North West	0	0	0
A828	Connel – South Ballachulish	North West	15	0	3
A830	Fort William – Mallaig	North West	8	0	0
A835/A893	Tore – Ullapool	North West	23	4	9
M876/A876	Dennyloanhead – Kilbagie Roundabout	South East	6	0	2
A887	Invermoriston – Moriston	North West	0	0	0
A889	Dalwhinnie – Laggan Bridge	North West	1	0	0
M898/A898	Erskine Bridge	South West	2	0	0
M9/A9	Edinburgh – Stirling- Thurso	South East/North Easth	125	14	37
M90/A90/A9000	Edinburgh – Fraserburgh	FBOC/North East	284	4	212
A956	Aberdeen Western Peripheral Route	North East	0	0	0
A92	East Fife Regional Road	North East	55	4	20
A92 /A972	Kirkcaldy – Dundee	North East			
A92	Stonehaven – Blackdog	North East			
A95	Granish – Keith	North East	11	0	7
A96	Aberdeen – Inverness	North East	98	0	53

A977	Longannet – Gartarry	South East	8	0	2
A985	Kincardine – Rosyth	South East	8	0	1
A99	Latheron – Wick	North West	11	0	3

Appendix B.

B.1. Questionnaire for Operating Companies

Appendix C.

C.1. Shanghai Case Study:

2016, Jie Yin, Dapeng Yu, Zhane Yin, Min Liu and Qing He (2016) “Evaluating the impact and risk of pluvial flash flood on intra-urban road network: A case study in the city center of Shanghai, China”, Journal of Hydrology, 637, pp. 138-145

In 2016 a study was conducted to evaluate the of risk and impact of flash flooding in Shanghai city centre, funded by the Open Research Fund of State Key Laboratory of Estuarine and Coastal Research, the National Natural Science Foundation in China, Project of Joint Centre for Shanghai Meteorological Science and Technology and the Innovation Program of Shanghai Municipal Education Commission.

The main aims of the study were to develop an approach to investigate the transportation impact from temporary pluvial flooding, understand the spatio-temporal characteristics of pluvial flash flooding on the road network in Shanghai city centre, and to quantify the disruption risk on transportation under a range of surface water flooding magnitudes.

Shanghai was chosen as the study area due to its high risk of pluvial flash flooding and associated impact of transportation disruption. Area is 32.5km2 of north part of Huangpu District with a mild and low-lying topography. The area has a northern subtropical monsoon climate, with annual average rainfall of 1122mm. The area is also affected by cyclonic storms and intense convectional precipitation occurring during flood season.

Pluvial flooding accounted for more than half of the total flood events from 251 -2000 in Shanghai, mostly in urban area. The study area has considerable areas of impervious surface except a few green open spaces.

For the purposes of modelling data acquired included an existing Intensity-Duration-Frequency (IDF) relationship models for local precipitations were available from municipal authorities in most Chinese cities. IDF formula for Shanghai developed by Shanghai Municipal Engineering Design Institute and applied for municipal drainage design.

Elevation data used was LiDAR from the Shanghai Survey Bureau. LiDAR cloud points were gathered in 2006. The error margin of this dataset was a root mean square error vertical of about 0.1m and a diameter of about 0.6m between each elevation point. The existing LiDAR data was then “cleaned” to remove urban surface features e.g. trees using TerraSolid software. As a final step in the processing, the point cloud was converted to a 2m resolution DSM grid for analysis.

Road data was acquired from the GIS lab at Ministry of Education and East China Normal University. It was further rectified to match the elevation data by manual visual interpreting in online maps. The urban roadway data was structured according specific known functions: main roads (30-40m wide), secondary main roads (20-24m wide) and side roads (14m to 18m wide). The road system contains more than 60 roads and 300 road sections with total length of 43.2km.

Rainfall intensities with duration of 1 hour, for the return periods of 1 in 5, 1 in 20, 1in 50 and 1 in 100 years were formulated to cover the probable inundation situations. These were calculated using the Chicago Design Storm, which is used extensively in the design storm, to get peak intensity and redistributes the rainfall before and after the peak with relevant spectrum of durations. A combination of IDF and Chicago methods to attain design storms for model.

FloodMap-HydroInundation2D used for study, which is an established 2D inundation model which couples hydrological processes and flood inundation to accurate model pluvial flooding in a high resolution. This was used to understand the flood risk to the urban road network. Runoff loss to the sewerage system was also considered in the model.

Due to a lack of remote sensing observations or reliable field surveys for historical pluvial flood events were not available for the study area so the model was calibrated using a comparison of a model prediction of a recent pluvial flash flood event against public reported flood incidents in the study area.

Road impact was identified against the findings from flood modelling. Road network links with a critical threshold of 30cm (based on car’s air inlet heights which are typically 25-35cm and frequently used as a basis for road closures in cities) was used to determine the relationship between inundation depth. Start and total duration for the grids when the water depths rise to 30cm were extracted from the model. A simple rule to represent the magnitude of flood-induced road interruptions by combining the submerged road length with its duration. Following this the probability of road risk of each scenario of each flood event was calculated. A risk assessment model based on economical assessment was not possible due to a lack of reliable data. Instead, risk was calculated using a proxy D_r (km h) to represent the magnitude of flood-induced road interruptions by combining the submerged road length with its duration. For each duration this was multiplied against the occurrence probability. Annual risk curves were generated by plotting the D_r multiplied by the event occurrence probability, and fitting a best fit trend against these points.

The average annual road risk of each scenario is defined by the area under the risk curve generated from the above methodology which is reflected by the equation in Figure XX below:

$$\mathrm{AAD}_r = \int f(x)D(x)dx \qquad (4)$$

where $f(x)$ is the probability function of a specific pluvial flood event x and $D(x)$ is the road impacts of x.

Figure A1-A: Average Annual Road Inundation Risk over all flood return periods

The study found that the road network in central Shanghai the maximum inundation extents and depths for road networks gradually increase with increasing recurrence intervals. Areas were there is low drainage capacity were observed to have the greatest inundation (>20cm depth) during 5 and 10 year rainfall events, which were considered to be higher in frequency. The entire network is also sensitive to low frequency flood events due to the lack of capacity in the local drainage systems. The extent of inundation of more than 0.3m depth may increase to 5 times between a 5 year and a 100 year flood event. It also found that the recovery time of the transportation network from disruptions is significantly longer for low frequency flood events, with models showing much of road networks being submerged even at the end of model simulation run times in 100 year flood event scenarios. Connectivity in the road network also caused a difference in the disruption times, with areas with more available diversions suffering less in the risk analysis than lesser-connected in the Central Business District of Shanghai through indirect disruption from inundation other sections of road.

The study provides a detailed approach to identify the impact and risk of pluvial flooding using pluvial flood numerical modelling, GIS-based road failure analysis and risk assessment modelling. However it should be noted this approach is not applied to arterial routes or the trunk road network, and the study area was in a concentrated urban area which is dissimilar to the trunk road network in Scotland. The model used in this approach also is reliant on reliable drainage models that have been calibrated, which are possibly more data and time intensive to create for the purposes of a trunk road network. Finally, the model in this study required reliable incident data for the purposes of calibration, which has been a known limitation of existing incident data for flooding as recorded by OCs for Transport Scotland.

C.2. Poland Case Study

Sweranski, S., Chruscinski, J., Kazak, J., Swiader, M., Tokarczyk-Dorociak, K., and Zmuda, R. (2018) "Pluvial Flood Risk Assessment Tool (PRFA) for Rainwater Management and Adaptation to Climate Change in Newly Urbanised Areas", Water, 10, 386, pp 1-20

This study consists of a literature review of existing pluvial flood risk assessment tools and methodologies as well as the development of the Pluvial Flood Risk Assessment tool (PFRA) for rainwater management and adaptation to projected climate change in newly-urbanised areas. The tool identifies areas vulnerable to pluvial flooding and presents the pluvial flood risk on risk maps. The aim of the tool is to support urban planning, decision makers and landscape designers for new developments. A study area in the village of Dobrzykowice to the north-east of the city of Wroclaw in Poland.

The PFRA developed uses GIS geoprocessing, spatial analytics, terrain surface, and hydraulic analysis as well as results of climate change modelling. It begins with using the ArcHydro extension in ArcGIS to determine volume of surface runoff, and using the extent and depth values of closed drainage areas for hydrological sinks to inform hazard and vulnerability assessments. The output of the hazard and vulnerability assessments is then fed into a risk score for local flooding. A Python script was used to generate output from the various models within the PRFA tool within arcGIS. The framework for the PRFA is visualised in Figure C-1.

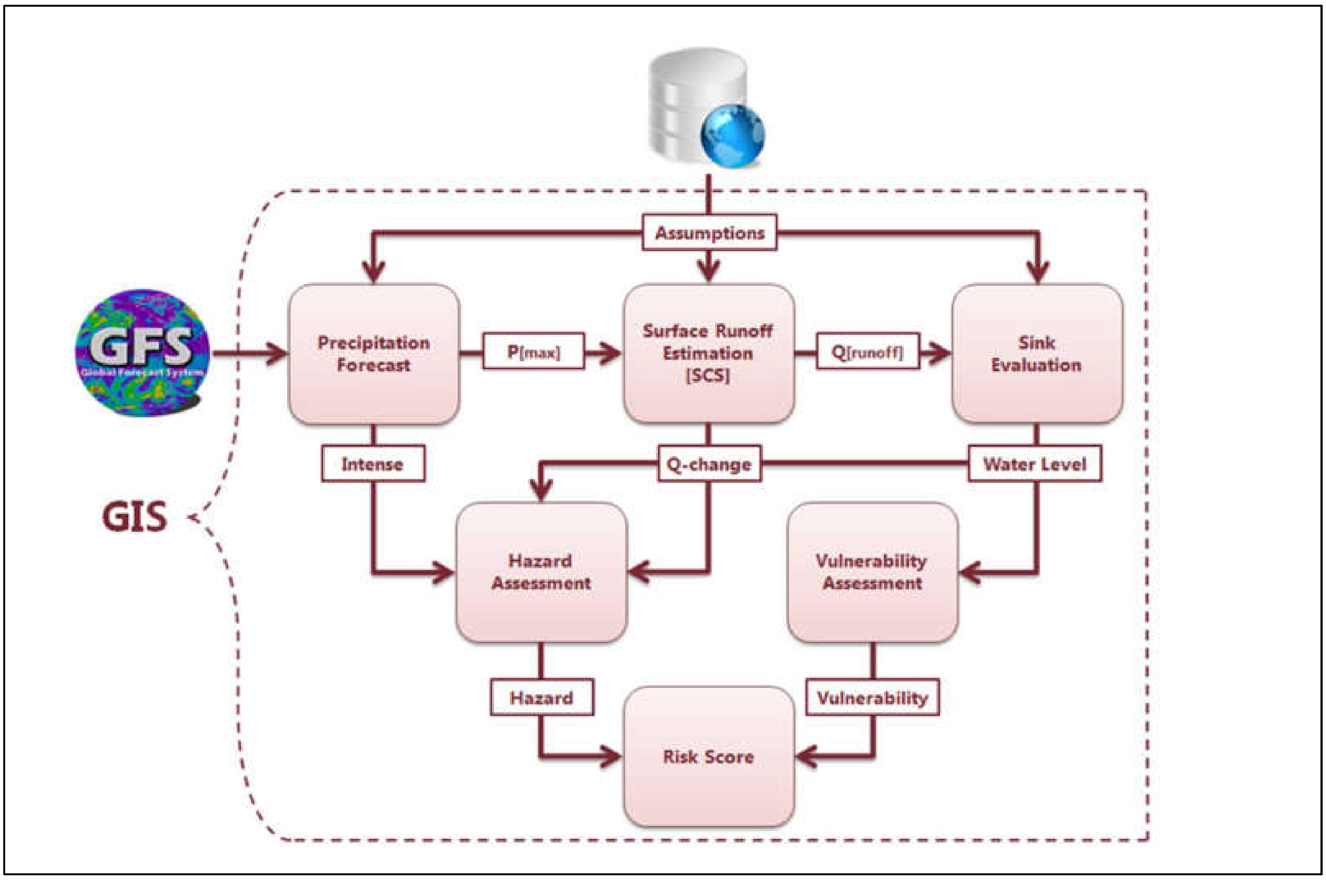


Figure C-1 - Research framework of Pluvial Flood Risk Assessment (PFRA)

Data used:

Spatial data input into the model included soil type and its infiltration capacity, land use and land cover, height of predicted precipitation, and topography. It also utilised land cover and land use codification from the

European Urban Atlas data. Spatial data was enhanced by the use of geodetic maps at a reference scale of 1:2000. The PRFA model did no incorporate data on sewage system capacity.

Rainfall data was automatically checked by the programme for maximum rainfall from the Global Forecast System. Data was available in three hour time steps, and was initially acquired in a Gridded Information in Binary (GRIB) format before further processing. The study acknowledges that one of the main limitations is the need for elevation data to be input in raster format only. Final resolution of any resulting maps is dependant on the resolution of input data used. There is also some uncertainty as to the level of accuracy of input data at a greater scale than the local study area, which is relatively small at 5 km^2, in this study.

Hazard levels were assigned based on a parameter of “Intense” rainfall when maximum precipitation exceeded 25mm. Critical depths for asset inundation was dependent on the type of assets – for example, critical value for the inundation at basements defined as 0 cm compared to 10 cm being the height of flood that would be a threat of entry into buildings. A percentage rate of predicted damage to buildings and interiors was applied to all affected assets in the study area. Finally, risk scores were formulated using the hazard and vulnerability parameters generated earlier in the model, as well as exposure.

Definition of the parameter of exposure is complex with difficulties in determining, amongst other variables, the evaporation properties for each flooded area and human mitigating actions that allow for quicker draining of flood water in affected areas. As such, exposition was simplified for the purposes of modelling to be any area that was affected by flooding.

In the study area, the model assigns highest risk to roads and associated land at all levels of input precipitation. Several areas that are identified as hotspots by the municipal authority through empirical reports of pluvial flooding were also identified as high risk areas in the model. The model also picked up areas of potential high risk to pluvial flooding that have not been reported for flooding by residents in the village. The study concludes that the PFRA model is therefore an appropriate method for assessing quantitative risk of local pluvial floods. The wide use of ArcGIS was also seen as enabling different types of organisations to be able to utilise this methodology.

A limitation on the accuracy of the model is the lack of drainage system consideration, water erosive capacity and water velocities. The model also failed to function when input vector data had poor typological accuracy, for example overlapping soil types in soil data. The study also acknowledges that local coefficients are better suited to quantify pluvial flood-related damages to be used in the calculations than the estimates used for the purposes of the study area.

Another limiting factor of using this methodology are the technical limitations of the ArcGIS pack applications which have an upper limit of 2 billion records per table, meaning application over very large areas might not produce appropriate output. Resulting ArcGIS databases were also large after input of all data required for the assessment, leading a requirement for high computer processing power. It is recommended that this methodology is enhanced in future with the use of radar rainfall data which would enable more real time flood forecasting. An advantage of the methodology is that the model is based on open source code and can be tweaked to optimise modelling for different users.

C.3. Review of EWS Worldwide Study

Acosta-Coll, M., Ballester-Merelo, F., Martinez-Peiro, M. and De la Hoz-Franco, E. (2018) “Real-Time Early Warning System Design for Pluvial Flash Floods – A Review”, Sensors, 2018, 18, 2255

This study reviews of Early Warning Systems (EWS) worldwide, primarily in countries that are worst affected to disasters in urban areas and provides guidelines to help develop an effective EWS for pluvial flash floods in real time. The causes and factors involved in flash flooding in urban areas are described, and it outlines the limited information available for EWS design. The study also examines the physical requirements to set up an EWS and the requirements of an appropriate communication-dissemination system for the community to receive timely updates before a flash flooding event. A basic structure for an effective EWS for pluvial flash flooding is recommended, considering the variables described above.

Pluvial or surface water flooding is defined as a problem in primarily urban areas and cities and occurs when high intensity rainfall overwhelms the capacity sewerage and drainage systems. This is coupled with decreases in soil absorption which comes with less permeable areas in cities. It reports that fluvial flooding has increased in urban areas and has the highest proportion of occurrence since 2000 compared to other types of flooding in the same period. It is also observed in the literature review that deficient drainage in cities, pluvial floods can turn into dangerous flash floods as in Baranquilla in Colombia, where streets become channels for high intensity rainfall causing a risk to life for pedestrians and roads users.

The literature review of this study also notes that pluvial flash flooding is not simply caused by weather phenomena but is also dependent on hydrological characteristics of the basin such as antecedent moisture conditions, soil type and land. Water level and water velocities noted to be the variables that affect the loss of stability of people and vehicles in the event of flash flood, and it is recommended that it is necessary for EWS to measure these variables in real time.

Early Warning System Basic Architecture

The authors of this study divide the architecture for what is considered an effective Early Warning system into 4 elements, these are:

1. Disaster-Risk Knowledge
2. Forecasting
3. Dissemination- Communication
4. Preparedness-Response

For the first element of Disaster-Risk Knowledge, the study states that it is necessary to identify the hazards, exposure, vulnerabilities and risks for a population. It suggests mapping trends and patterns in flood risk to inform the prioritisation of EWS in appropriate areas. This is described as a two-step process. Firstly, data processing, establishment of modelling to determine runoff and probability analysis is to be conducted. Secondly, interviews, discussion groups and workshops are to be conducted with the at-risk community groups to determine vulnerability. This second step should take into account historical records and community perceptions.

The study breaks Forecasting down into 2 sub-elements: Monitoring and Information Processing. Monitoring is the part of forecasting that monitors and transmits information on meteorological and hydraulic variables that affect urban flash floods. Information Processing, on the other hand, receives the data of the abovementioned variables and formulates alerts through analysis tools, computer models and simulations. Forecasting is defined as needing to address whether right parameters are being monitored, whether there is a scientific basis for making the forecasts and whether accurate and timely warnings can be generated from these forecasts.

Dissemination and communication systems are considered an important next step to ensure adequate responses that allow for safety around high intensity rainfall events and allow the preservation of lives and livelihoods. To this end, information communicated to at-risk groups needs to be clear, simple, and useful. Detailed threat information using localised geographic references should be included and multiple channels should be used for the delivery of information to reduce delays to users and ensure as broad a group of users can be reaches as possible. The paper provides a case study of Hong Kong, where multiple users, broken down into several demographic groups, are surveyed as to their preferred channel for disaster information. Channels included in the survey were television, social media, radio, news agency websites and government websites. Perceived credibility of each source of information for the end user was also considered.

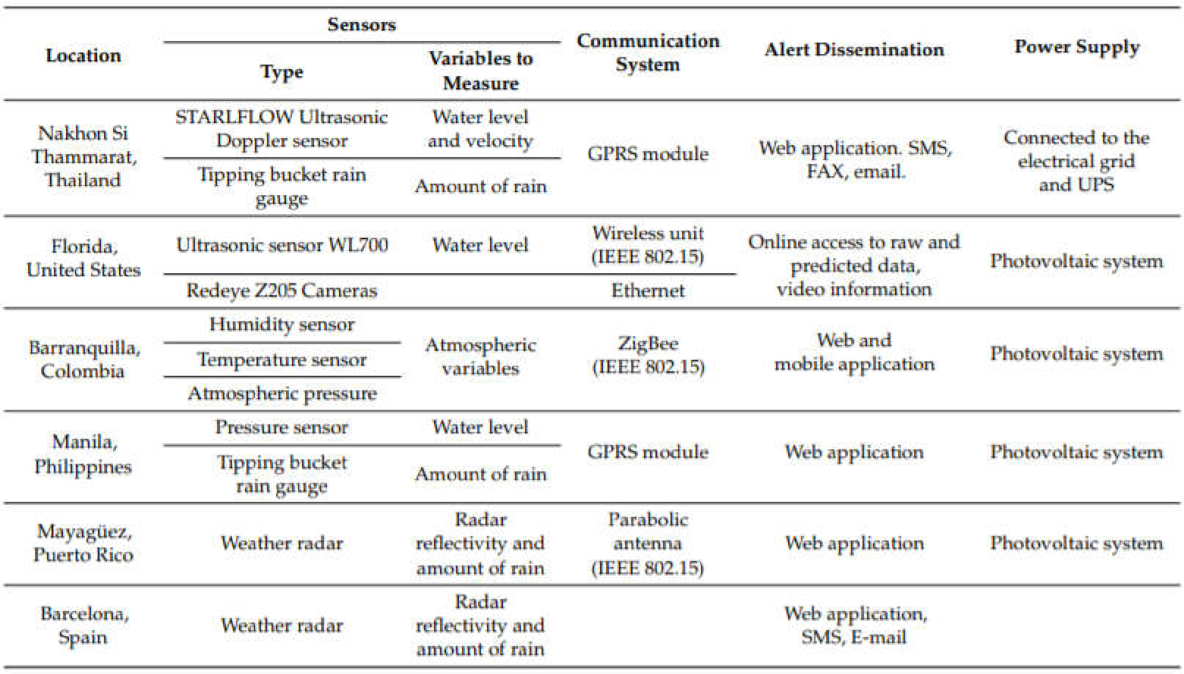
Preparation-Response is defined as the end-user's capability to understand and act upon weather and risk information as shared in the Dissemination-Communication process. The paper further examines a case study in Boulder, Colorado on the response to flash flood warnings, and concludes that it is not only necessary to notify end-users of the danger of a flood, but to motivate them to take appropriate action in response to this.

Real-Time Early Warning Systems:

The paper examines six existing real-time early warning systems. These are located in:

1. Nakhon, Si Thammarat, Thailand
2. Florida, United States
3. Baranquilla, Colombia
4. Manila, Philippines
5. Mayaguez, Puerto Rico
6. Barcelona, Spain

A review of each of these was undertaken to assess the variables that are considered in each of the EWS in each location, technology used for this, communication protocols of this data, and alert dissemination in the event of a forecast flood. This is summarized in Figure C-2 below:



Location	**Sensors**		**Communication System**	**Alert Dissemination**	**Power Supply**
	Type	**Variables to Measure**			
Nakhon Si Thammarat, Thailand	STARLFLOW Ultrasonic Doppler sensor	Water level and velocity	GPRS module	Web application. SMS, FAX, email.	Connected to the electrical grid and UPS
	Tipping bucket rain gauge	Amount of rain			
Florida, United States	Ultrasonic sensor WL700	Water level	Wireless unit (IEEE 802.15)	Online access to raw and predicted data, video information	Photovoltaic system
	Redeye Z205 Cameras		Ethernet		
Barranquilla, Colombia	Humidity sensor	Atmospheric variables	ZigBee (IEEE 802.15)	Web and mobile application	Photovoltaic system
	Temperature sensor				
	Atmospheric pressure				
Manila, Philippines	Pressure sensor	Water level	GPRS module	Web application	Photovoltaic system
	Tipping bucket rain gauge	Amount of rain			
Mayagüez, Puerto Rico	Weather radar	Radar reflectivity and amount of rain	Parabolic antenna (IEEE 802.15)	Web application	Photovoltaic system
Barcelona, Spain	Weather radar	Radar reflectivity and amount of rain		Web application, SMS, E-mail	

Figure C-2 - Instruments, communication protocols and alert dissemination

In general, EWS seemed to be divided into being driven by two different types of input data where rainfall was considered – amount of rain from radar data versus real time monitoring using tipping bucket rain gauges at local sites. Radar data was considered to be more appropriate for systems that were designed for high coverage however the cost of the data and amount of processing for data of this size was considered to be a barrier to using this data in smaller scale monitoring. Radar data was also considered to provide more lead time for the forecasting system, and to be a good back up for other data collection assets which can suffer from tampering or theft on site.

Three EWS examined included sensors for water level, inclusive pressure sensors and ultrasonic sensors. Pressure sensors were used in the Manila case study, which was specifically to allow for the rerouting of traffic at 2 road network hotspots in the event of flooding. The benefits of using ultrasonic sensors was that pressure sensors are submerged and can be affected by debris in floodwater that can lead to erroneous measurements and damage to the sensor, which is not a factor that affects them. However, ultrasonic sensors are unable to function under water and measurements can be affected by variables such as air temperature and humidity which can lead to affect accuracy.

Most of the reviewed systems used wireless systems to transmit the data collected, however they appeared to only have one mode of data transmission which was perceived to run the risk of failing to adequately provide warning in the event of the system failing. Most systems also used photovoltaic systems to power the sensors that collected data, which was deemed more reliable to prevent sensor failure in the event of power interruptions from flood events. One EWS used a direct connection to the electrical grid however this was backed up using an uninterruptible power supply (UPS) which allows the equipment to work for at least 24 hours without a continuous power supply.

Information collected for all methods are then processed in a data sensor after transmission, which is equipped with applications and analysis software necessary for alert design. In terms of dissemination method, most of the EWS reviewed web applications, mobile applications and to a lesser extent SMS and email alerts. This does not consider channels such as television and radio that would better cater for older members of the demographic that are less technologically savvy.

Conclusions:

The paper involves a comprehensive review of existing EWS for pluvial flash flooding in several countries from different regions. However the pluvial flash flooding examined in most of the case studies are confined to cities and urban areas that aren’t trunk road locations. The Manila case study has the most similarities to the type of early warning system and flood forecasting desired in the scope of this Transport Scotland study.

The assumptions regarding cost of technology for the data collection in flood forecasting may also differ in comparison to the Scottish context. For example, installation of raingauges and level sensors at all areas regarded vulnerable to flooding may be, in reality, a more expensive way of monitoring due to the large area over which the trunk road network is spread out. Radar rainfall data is also freely available in the UK from the UK Met Office, eliminating the problem of cost for utilisation radar data as highlighted by the authors of the paper.

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