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Identifying pressures • Informing policy • Developing solutions

FloodWarnTech Synthesis Report: Flood Warning Technologies for Ireland

Authors: Michael Bruen and Mawuli Dzakpasu

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Rialtas na hÉireann
Government of Ireland

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EPA RESEARCH PROGRAMME 2014–2020

FloodWarnTech Synthesis Report: Flood Warning Technologies for Ireland

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Prepared for the Environmental Protection Agency

by

University College Dublin

Authors:

Michael Bruen and Mawuli Dzakpasu

ENVIRONMENTAL PROTECTION AGENCY
An Ghníomhaireacht um Chaomhnú Comhshaoil
PO Box 3000, Johnstown Castle, Co.Wexford, Ireland

Telephone: +353 53 916 0600 Fax: +353 53 916 0699
Email: info@epa.ie Website: www.epa.ie

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Cover image - Ballinasloe, River Suck in flood November 2009, photo taken by Pat Durkin, EPA

The EPA Research Programme addresses the need for research in Ireland to inform policymakers and other stakeholders on a range of questions in relation to environmental protection. These reports are intended as contributions to the necessary debate on the protection of the environment.

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Project Partners

Professor Michael Bruen (Principal Investigator)
School of Civil Engineering
University College Dublin
Dublin 4
Ireland
Tel.: +353 1 716 3212
Email: michael.bruen@ucd.ie

Dr Mawuli Dzakpasu
School of Civil Engineering
University College Dublin
Dublin 4
Ireland
Tel.: +353 1 716 3212
Email: mawuli_dzkps@yahoo.com.au

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Executive Summary

FloodWarnTech was an Environmental Protection Agency (EPA)-funded desk study of flood warning, with a specific focus on Ireland. Its objectives were to investigate (1) flood forecasting techniques and systems in use in Ireland and elsewhere; (2) methods and models best suited for use in Ireland; and (3) the optimal use of relevant data sources, observations and forecasts for flood forecasting.

The project started with an extensive review of the topic and of existing forecasting systems. It held a well-attended workshop at which (1) invited experts described some of the internationally available flood warning platforms, suitable for use in Ireland, and (2) an opportunity was provided for potential users of warning systems and for stakeholders, from a wide range of emergency responder organisations, to discuss their forecasting and warning requirements. The workshop agreed on the need for further data collection, improved modelling and also closer involvement of users, the public and the media. A desire was expressed for some forecast uncertainty information and flood response planning and river maintenance were identified as important aspects of the problem.

In addition, the project investigated, for three selected catchments, the value of different sources of precipitation information (rain gauges, radar and numerical weather models) as inputs to hydrological models to simulate river flows. This highlighted the continuing value and importance of the terrestrial rain-gauge network.

The project also demonstrated, with assistance from its developers, the use of an existing real-time flood forecasting system.

The conclusions from the project are as follows:

1. The proposed national flood warning service should be implemented as soon as possible.
2. This service should consider the broader aspects of flood warning identified by the workshop participants, listed above, especially the effective communication of warnings to the public and to decision makers. The generation and use of uncertainty information is recommended.
3. The rain-gauge network has a critical role to play in the performance of flood forecasting systems and should be preserved and enhanced where small catchments contribute to critical floods. This project did not have the resources to consider the use of X-band radar for these critical areas. This could be a separate study.
4. Both radar and numerical weather prediction (NWP) contribute value to flood forecasting, with the potential, particularly of NWP, to extend useful forecast lead times.

Suggestions for further investigations included:

1. The full MÉRA reanalysis data set is now available (the FloodWarnTech project had access only to a pre-release 3-year data set). The model simulations and data source tests carried out here should be extended and undertaken for the full duration of the data set. This would augment and/or strengthen the conclusions.
2. This project did not examine methods of assimilating upstream stream discharge into forecasting systems. For a number of the larger rivers in Ireland, this is potentially of value and should be investigated.

1 Introduction

1.1 Background: Flood and Flood Hazard

Flooding occurs when a body of water rises to overflow land that is not normally submerged (Ward, 1978). While this definition explicitly includes all types of surface inundation, floods are typically classified into four categories, viz., riverine (fluvial), coastal, groundwater and urban (often called pluvial) flooding. This study is limited to riverine floods, which occur when a river discharge exceeds its bankfull capacity (Leopold *et al*., 1964). Water levels increase above the bank level of the river and inundate its surroundings. Based on their nature and speed of occurrence, some pluvial floods are called flash floods and these typically occur within 6 hours of rainfall events. Short, intense bursts of rainfall, commonly from thunderstorms, typically cause such floods. Endangered communities normally have a limited response time. Other hazards, such as landslides and mudflows, often accompany flash floods, causing damage, physically to property and psychologically to people, and, in extreme situations, deaths. Fluvial flooding, on the other hand, is marked by relatively slowly rising water levels of main rivers and a gradual inundation of floodplains and is associated with longer duration rainfall (Ward, 1978; Maskey, 2004; Dingman, 2015). Flash floods present a more daunting challenge to the preparedness of flood-prone communities while the larger scope and longer duration of typical fluvial flooding constitutes a major challenge to the scale and endurance of disaster management arrangements (Rosenthal and Hart, 1998).

In the last decade, public and governmental concern has resulted in them demanding improved flood warnings (Penning-Rowsell *et al*., 2000; Handmer, 2001) and that the monetary benefits are recognised (Pappenberger *et al*., 2015). A recent review of climate change-related natural hazard and disaster vulnerabilities (Bruen and Dzakpasu, 2018) cites predictions of increases in the frequency and intensity of extreme precipitation events. These will lead to more severe flooding, which become more hazardous as urbanisation forces increasing populations into floodplains. Therefore, the need to develop forecasting systems with high spatial resolution and adequate lead time to cope with such increasing flood hazards cannot be overstated. Timely and accurate forecasts and warnings, are needed by emergency services and for public preparedness for, and their response to, flooding events.

Flood forecasting and warning systems share the basic functions of collecting, processing, analysing and disseminating hydrological information, ideally in real time (Bedient *et al*., 2013). Together, these functions can provide advance warnings of impending flood conditions. For river flooding in Ireland, rainfall is often a key input, although other meteorological factors may be required. These include observations or estimates of air temperature, wind speed, net and solar radiation and soil moisture (Sene, 2008). Additional data required may include reservoir and lake evaporation and, in other countries, snow cover, river ice cover and ice jam locations. Nonetheless, modern flood forecasting and warning systems have evolved to meet the distinct needs of different clients, regions or countries. Consequently, these systems and the organisations that oversee them differ considerably in complexity, size and scope.

Significant advances in flood forecasting have been achieved through a range of improvements in observation capabilities, modelling techniques and decision support systems. The most notable improvements are remote sensing observations, such as satellite and radar, and associated computer modelling techniques for processing these observations to produce lead times varying from hours to days. Some satellite-based precipitation products with high temporal and spatial resolution (near real time) have recently been developed. Advanced techniques have also been developed for deriving very high resolution (spatial and temporal) real-time rainfall estimates from weather radar data, either adjusted or merged with gauged rainfall.

New techniques have been developed for merging multiple sources of information to produce rainfall forecasts with extended lead times. These combine satellite-based rainfall, radar rainfall, gauged rainfall and numerical weather prediction (NWP) model outputs to produce rainfall forecasts. Recent improvements in the accuracy and resolution of NWP models have enhanced the quality of ensemble rainfall forecasts. Improved real-time rainfall estimates and forecasts give rise to the prospect of improved flood forecasts. This prospect is further enhanced by advances in the use of microwave satellite data to derive information on soil moisture (Owe *et al*., 2001; Alvarez-Garreton *et al*., 2014), evapotranspiration, land use (Karimi and Bastiaanssen, 2015), snowpack extent (Mhawej *et al*., 2014) and flood inundation areas (Lacava *et al*., 2015) to improve flood modelling.

At present, there is no operational flood forecasting service with national coverage in Ireland. Flood forecasting and warning services are provided on either a regional or a local basis. Regional services are provided by the European Flood Awareness System (EFAS), hosted by the European Centre for Medium-Range Weather Forecasts (ECMWF), and are available to the Office of Public Works (OPW). Local services are typically developed by the OPW and operated by local authorities in close co-operation with state and local government agencies. The national agencies, such as OPW, Met Éireann and Civil Defence, provide support services, such as information (in the form of warning products) and specialist support and advice. These include radar-based weather information, appropriate flood response and action plans, and support and guidance in the establishment of automated local flood warning systems. However, there is a need for a more efficient flood forecasting and warning system for the whole of Ireland (JBA Consulting, 2011). Such a system is in the planning stage and will help to cope with future events predicted to be more severe as a result of climate change (Bruen and Dzakpasu, 2018) and various other factors, including population growth and rapid urbanisation.

2 Input Data for Flood Forecasting

The main inputs that are required to a river flood forecasting model typically include river level or flow observations and precipitation estimates by rain gauge, weather radar or satellite data. This information is usually received by telemetry, although manual observations are also used. Rainfall forecasts are also increasingly used to extend lead times further, and forecasts for other variables are sometimes required, such as of air temperatures for use in snowmelt models.

2.1 Rainfall Estimates

In temperate regions, precipitation is the most significant factor influencing the frequency and magnitude of flooding events (Bloschl *et al*., 2015). Of the several strategies for flood alleviation that have been identified and applied in various flood mitigation schemes (Figure 2.1), one of the most important is the use of precipitation information in flood forecasting and warning. These depend largely on hydrological and hydraulic models for flow prediction (Takeuchi, 2001). A hydrological model, which conceptualises the complex physical characteristics of a basin (Dingman, 2015), is used to estimate stream flow rates and water levels in near real time as they respond to rainfall. The outputs from these models can provide flood warnings. Early warnings allow for adequate time to evacuate affected areas, shutdown vulnerable transportation infrastructure, install demountable barriers, deploy emergency workers and establish emergency short-term flood protection for vital structures (Looper and Vieux, 2012).

Hydrological modelling outputs contain significant uncertainties (Krzysztofowicz, 2001; Beven, 2010; McMillan *et al*., 2012; Dogulu *et al*., 2015) from uncertainties in the data, the model structure and its parameters, and the perceptual model of the underlying hydrological system (Dogulu *et al*., 2015). For rainfall, possible sources of uncertainty and error are the temporal and spatial variability (Faurès *et al*., 1995; Goodrich *et al*., 1995; Shah *et al*., 1996; AghaKouchak *et al*., 2010), which provides a critical challenge for hydrological forecasting.
In addition, accurate rainfall data is needed in model calibration to produce parameter sets that

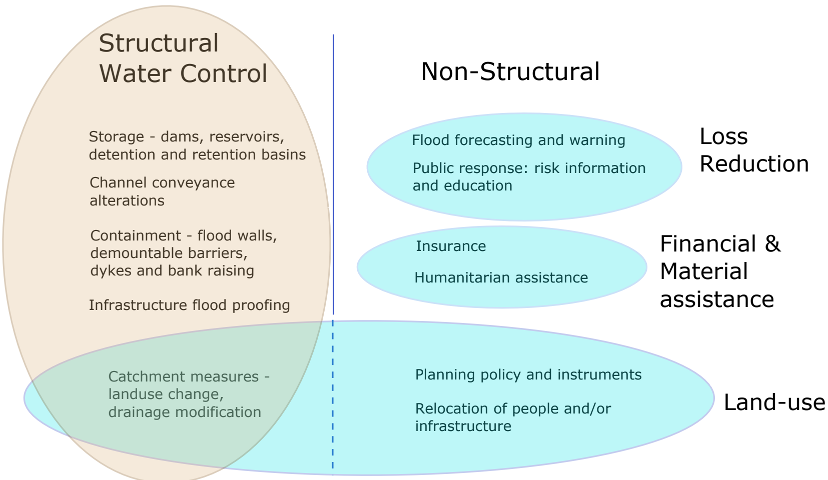

Figure 2.1. Alternative flood alleviation strategies.

represent basin characteristics. Widespread use of hydrological models has demonstrated the need for accurate rainfall fields to have confidence in runoff and streamflow predictions (Beven and Hornberger, 1982; Kalinga and Gan, 2006; Cole and Moore, 2008; Berne and Krajewski, 2013; Xu *et al*., 2013). No matter how well a model is founded in physical theory or empirically justified by past performance, it cannot produce accurate runoff predictions if forced with inaccurate rainfall data. Inaccurate rainfall data directly compromise the integrity of the model and the associated critical decisions (Golding, 2009). For small catchments, such as those typically found in Ireland, the timing and location of rainfall is critical in reproducing hydrographs. There is thus an urgent need to acquire reliable precipitation estimates at high spatial (e.g. a few kilometres or less) and temporal (e.g. hourly or less) resolutions (Berne and Krajewski, 2013).

2.1.1 Rainfall estimation by rain gauges

Rain gauges are the most popular and widely used method for recording rainfall accumulations at a single location. While they can provide accurate point measurements, they are subject to numerous sources of error and uncertainty, which limit their use in operational flood forecasting models (Wilson and Brandes, 1979; Sinclair and Pegram, 2005). These relate to the inability of rain gauges to capture the spatial variability of a rainfall field. Moreover, systematic and calibration errors affect the accuracy of rain gauges through evaporative losses, splash-out, wind effects, valley effects, tree and building cover or miscalibration.

Distributed hydrological models require a spatial distribution of rainfall over entire catchments. Rain gauges can provide only a fractional coverage of the entire spatial domain and are thus often unable to provide an accurate representation of the variability in a large rainfall field. Consequently, a network of gauges is used to produce the spatial distribution and to interpolate rainfall accumulations at ungauged locations. However, this spatial variability cannot be adequately captured through the interpolation of point rain gauge values (Sinclair and Pegram, 2005). The interpolation accuracy of rainfall datasets depends on having an optimal network density and spacing (Rodriguez-Iturbe and Mejia, 1974; Xu *et al*., 2013). However, optimal gauge density and spacing is, for the most part, never achieved in river basins (Smith *et al*., 2007). Economic and practical considerations result in limited gauge networks that usually give a poor representation of the rainfall field over the basin (Volkmann *et al*., 2010). A rain gauge network density of one gauge per 65 km^2 is recommended (Huff, 1970) to achieve an average sampling error of less than 5% in recorded 6-hour rainfall accumulations. The density required, however, changes according to operational considerations. WMO (2008), on the other hand, recommends rain gauge densities according to catchment type at one gauge per 250 km^2 for mountainous catchments or at one gauge per 900 km^2 for flat catchments. The US Army Corps of Engineers (1996) recommends a network design with evenly distributed gauges at a spatial density determined by equation 2.1:

$$N = A^{0.33} \qquad (2.1)$$

where N is the number of gauges and A is the area of the basin (in square miles).

Other factors that can affect the optimal network density of rain gauges include climatic patterns, topography (Lobligeois *et al*., 2014), typical storm type (Huff, 1970) and character of extreme rainfall events (Barge *et al*., 1979). In the unique case of localised rainfall events, a dense rain gauge network is desirable for operational flood forecasting. However, the installation of such a network may be impractical (Zhu *et al*., 2013). Therefore, rainfall is often mischaracterised during high-intensity, small spatial-scale events, leading to significant errors in predicted stream flows (Golding, 2009). Several methodologies have been developed to optimise the location and density of rain gauge networks (Pardo-Iguzquiza, 1998; Jung *et al*., 2014).

The high variability in rainfall fields has a demonstrated effect on runoff modelling (Schilling and Fuchs, 1986; Faures *et al*., 1995). In areas dominated by high-intensity rainfall events with significant spatial variability, rain gauge density and placement can strongly influence the predicted stream flows from hydrological modelling, leading to increased uncertainty in model outputs. This can have detrimental consequences for the use of rainfall estimates from rain gauges alone as input into hydrological models for flood forecasting, which has led to calls for the improvement of rainfall estimation

(Wilson and Brandes, 1979; Kouwen, 1988; Borga *et al*., 2000, 2002; Beven, 2002; Goudenhoofdt and Delobbe, 2009; Looper and Vieux, 2012). These calls have led to the investigation of other methods to increase the accuracy of rainfall estimation.

In Ireland, Met Éireann co-ordinates rainfall measurements in Ireland with data collected from its own rain gauges and those operated by individual volunteers and organisations. Rainfall data are collected hourly, daily or monthly. The majority of the approximately 750 rain gauges located throughout Ireland are read daily. The remainder are monthly read gauges located in remote areas. Monthly readings are of little value to flood forecasting. Met Éireann makes hourly rainfall data available on its website from 25 locations. These provide valuable information on rainfall intensity. However, the spatial distribution of these may be inadequate for the needs of a national flood forecasting service.

Met Éireann also operates two weather radar systems that can provide precipitation estimates. Currently, the radar images are mainly used subjectively to assess the areas of intense rain and to track the movement of rain storms. Furthermore, Met Éireann operates a high-resolution NWP model. However, the existing flood forecasting systems in Ireland do not currently use rainfall estimates derived from both radar and NWP models. The availability of rainfall forecasts based on multiple sources of information provides an impetus for developing a national flood forecasting system as well as for improving the existing flood forecasting systems, as is shown in this project.

2.1.2 Rainfall estimation by radar

Weather radars can produce estimates of precipitation over large geographical areas using measurements of reflectivity and can therefore provide information about rainfall patterns at high temporal and spatial resolution. Furthermore, radars can provide rapid updates of the three-dimensional structure of precipitation. These advantages led to more wide-spread operational usage of radar precipitation measurements. Their potential applications for hydrological modelling have been the subject of extensive research (Browning, 1978; Bonnifait *et al*., 2009; Cole and Moore, 2009; Collier, 2009; Viviroli *et al*., 2009; Looper and Vieux, 2012; Keblouti *et al*., 2013).

The use of radar for quantitative precipitation estimation (QPE) in hydrological models began in the early 1960s, when the spatial distribution of radar information markedly improved real-time flash flood warning in comparison with rain gauge data (Wilson and Brandes, 1979). Since then, many studies (e.g. Vehviläinen *et al*., 2000; Cranston and Black, 2006; Smith *et al*., 2007; Looper and Vieux, 2012) have demonstrated how radar estimates substantially increased the accuracy of flood forecasting hydrological models during extreme rainfall events. Collier (1986) demonstrated that a rain gauge network spacing of one gauge per 20 km^2 was needed to provide a spatial distribution of the rainfall field as accurately as radar. However, despite these advantages in the early stages of its application, the lack of knowledge and understanding of the inaccuracies associated with radar imagery limited its widespread use for hydrological modelling (Jayakrishnan *et al*., 2004; Golding, 2009).

The uncertainties associated with radar QPE stem from their being an indirect measurement of rainfall and they thus are subject to multiple sources of error, e.g. radar beam blockage, beam power attenuation, ground clutter and anomalous propagation of the signal (Joss *et al*., 1990; Collier, 1996; Harrison *et al*., 2000; Michelson and Koistinen, 2000; Einfalt *et al*., 2004). Other factors include variability in time and space of the vertical profile of reflectivity (VPR) and issues related to the microphysics of precipitation, influencing the relationship between radar reflectivity and quantity of precipitation. Furthermore, spatiotemporal sampling errors can arise from the fact that radar beam measures rainfall at significant heights above the ground. Between the measurement location and the ground, the rainfall can move substantial lateral distances or even evaporate before reaching the ground. Electromagnetic interferences, e.g. from wi-fi systems, may also influence performance, potentially degrading the quality of rainfall estimates.

Gauge-based adjustment of radar QPEs has proven effective in reducing these errors and improving the accuracy of the estimates and thus their applicability for hydrological applications (Steiner *et* al., 1999; Harrison *et al*., 2009). However, most gauge-based adjustment methods have been tested and applied at large spatial and temporal scales (Smith and Seo, 1996; Fulton *et al*., 1998; Anagnostou *et al*., 1999;

Todini, 2001; Germann *et al*., 2002, 2006; Gerstner and Heinemann, 2008; Goudenhoofdt and Delobbe, 2009; Harrison *et al*., 2009). The relatively few tests that have been conducted at urban/small scales report that at these scales more dynamic and localised adjustments are required (Wood *et al*., 2000; Sinclair and Pegram, 2005; Chumchean *et al*., 2006; Borup *et al*., 2009; Wang *et al*., 2013; Löwe *et al*., 2014).

2.1.3 Effect of radar uncertainty on hydrological forecasting

The uncertainties of radar QPE owing to the errors of calibration and processing have detrimental effects on the quality of hydrological modelling forecasts. For example, Kouwen and Garland (1989) reported that anomalous propagation, clutter and visibility effects caused significant errors in the QPE, which led to an about 10% overestimation of the predicted peak flows. Similarly, Borga *et al*. (2002) reported that range-related errors, VPR effects and errors due to miscalibration of the Marshall–Palmer Z–R relationship significantly affected streamflow simulations, resulting in errors of similar magnitude to those in gauge-only simulations. However, Krajewski *et al*. (2010) showed that improvements in radar hardware and software have improved the quality of radar QPE significantly. Nonetheless, radar data need significant correction before use in hydrological forecasting (Jayakrishnan *et al*., 2004; Neary *et al*., 2004).

On the other hand, the impacts of radar-derived QPE on the accuracy of hydrological model outputs are significantly higher in small catchments, particularly in urban areas, than in larger basins (Bell and Moore, 1998; Collier, 2009; Schellart *et al*., 2010, 2012, 2014). According to Vehviläinen *et al*. (2004), in small catchments of less than 500 km^2 where response times are of the order of hours, hydrological models can benefit from the high temporal and spatial resolution of radar data. However, mountainous topography can significantly impact on radar QPE by blocking radar beams, resulting in simulations of comparable accuracy in radar-driven hydrological model outputs as gauge only-driven results (Borga *et al*., 2000). Therefore, although the use of radar for QPE can potentially increase the accuracy of the rainfall input, an understanding of location-specific factors is required to determine the worth of the radar.

2.2 Merging of Gauge and Radar Rainfall Estimates

Several efforts have addressed the limitations associated with the gauge and radar rainfall estimation discussed in section 2.1 by merging their outputs. This merging seeks to build on the strengths of each method while reducing their individual weaknesses (Erdin, 2009). It has since been recognised that the combination and adjustment of radar rainfall data with rain gauge accumulations significantly improves the accuracy of rainfall estimates and subsequent hydrological modelling outputs (Kouwen 1988; Vehviläinen *et al*., 2004; Kalinga and Gan, 2006; Kim *et al*., 2008; Looper and Vieux, 2012). Some techniques for merging gauge and radar estimates have thus been developed for operational use, which can be classified broadly into two categories, namely bias reduction and error variance minimisation (Wang *et al*., 2013). Nevertheless, these merging techniques have been shown to improve accuracy mainly at time steps greater than 1 hour. At time steps of less than an hour, the accuracy approaches that of raw radar alone on account of spatiotemporal sampling errors involved in the direct comparison of radar and gauges.

2.3 Rainfall Forecasts

Accuracy and lead time of precipitation forecasts are vitally important parameters of any flood forecasting system. Without precipitation forecasts, the warning lead time is limited to the catchment response time, which depends on catchment morphology, size and land use. Skilful forecasts of precipitation are required for effective warning of flash flooding in small, fast-responding catchments and for extending the flood warning lead times in other catchments. Developments in quantitative precipitation forecasting (QPF) techniques have proven valuable for many hydrometeorological applications (Zahraei *et al*., 2013). The real benefit of QPFs, however, depend on the lead time of the forecasts, which range from very short (1–6 hours) and short (12–72 hours) to medium (72–240 hours) (Cuo *et al*., 2011). For example, high-resolution QPFs with lead times of 1–6 hours enhances forecasting and warnings for flash flooding (Hapuarachchi *et al*., 2011) and flooding in small, fast-responding catchments. In small catchments, forecasts based on observed discharge is of little practical use on account of the very short lead time

(Ehret, 2003). Forecasts based on observed discharge combined with a rainfall–runoff model using observed precipitation have a slightly increased lead time. Unfortunately, because of the short concentration times, even this is often insufficient to take effective preventive actions.

While QPF provides possibilities of extending the forecast lead times, current computational constraints restrict their operational forecast update cycles to hours (e.g. every 6 hours), whereas convective phenomena typically exhibit life times of tens of minutes (Browning, 1979). Short-time forecasts of a few hours can be based on radar data using statistical methods. On account of the uncertainties and errors associated with radar rainfall measurements, reasonable forecasts can only be achieved if radar precipitation is combined with surface observations of rainfall. These combined rainfall rates with their high spatial and temporal resolution can be used to develop reasonable rainfall forecasts. These forecasts can then be put into rainfall–runoff models to provide discharge forecasts. Thus, QPFs enable the modelling of runoff and flow processes at a longer lead time to control the critical situations of flood-induced damage based on adequate control decisions (Krämer and Verworn, 2009). Two approaches with different time scales of applicability are in use for QPF, namely forecasting by NWP and forecasting of rainfall by extrapolation from weather radar rainfall estimates (called radar nowcasting).

Nowcasting emphasises the short-term nature of the forecast of 0–6 hours (Wilson *et al*., 2004) at high spatial (e.g. 1 km) and temporal (e.g. 5 minutes) resolutions (Liguori and Rico-Ramirez, 2013). Nowcasting is usually based on the analysis of a short series of radar images providing estimated rainfall distributions at consecutive times, which are extrapolated into future rainfall patterns. They are characterised by a good accuracy at the start of the forecast, as the precipitation is observed directly, which decreases very rapidly with lead time, as the basic extrapolation techniques generally do not account for growth and decay processes in the atmosphere (Golding, 1998). Nowcasts are potentially valuable in the predictions of quickly developing high-intensity rainfall events (Wilson *et al*., 2004), and are thus of vital importance in flood warnings and risk management for hydrometeorological events (Ruzanski, 2011). Although the hydrological application of nowcasts benefit from the high spatial and temporal resolution of the forecasts (Wilson *et al*., 1998), they, nevertheless, need to be balanced against the short-time range of applicability of the forecasts.

Numerical weather prediction uses models that resolve the dynamics and physics of the atmosphere on scales ranging from the global scale to the mesoscale and can provide predictions of rainfall as well as other meteorological quantities. Nevertheless, the increase in the resolution of NWP models and the need to improve the prediction of small-scale features by appropriate physical parameterisations presents a significant challenge in the hydrological application of NWP rainfall forecasts (Cloke and Pappenberger, 2009). Unlike radar nowcasts, NWP rainfall forecasts suffer from imperfect assimilation of the initial state of the atmosphere. NWP models typically suffer from "spinup" errors in the first few hours before settling (Golding, 1998). Many authors (e.g. Bowler *et al*., 2006; German *et al*., 2006) suggest that extrapolation-based precipitation nowcasts have superior skill compared with NWP forecasts for lead times up to 6 hours. However, recent findings (Ballard *et al*., 2016) demonstrate the potential for improved nowcasting using frequently updated initial conditions for convection-permitting NWP. Moreover, NWP ensemble prediction systems can exhibit greater forecast skill (Cloke and Pappenberger, 2009) than single NWP deterministic model runs. The ensembles increase forecast accuracy and allow for skilful predictions at longer lead times (Buizza *et al*., 1999; Demeritt *et al*., 2007). Furthermore, NWP model-based probability forecasts issued on consecutive days are usually more consistent than single-valued forecasts (Buizza, 2008). Therefore, although radar nowcasts are preferable for short forecast periods, NWP rainfall forecasts are preferable for long forecast periods (Lin *et al*., 2005).

Advances have been made in building hybrid forecast systems aimed at blending the different forecast capabilities of NWP and radar nowcasting systems with respect to the forecast lead time (Golding, 1998; Pierce *et al*., 2000). Recent advances have further exploited this approach to hybrid forecasting through the STEPS (Short-term Prediction System; Bowler *et al*., 2006) and SBMcast (Berenguer *et al*., 2011) models. Data assimilation into NWP models offers the ability to use all observations up to the present to get the best estimate of the state of the atmosphere, from which nowcasts are produced. Currently, nudging, variational data assimilation (3D-Var and 4D-Var) and ensemble Kalman filters (EnKF) for high-resolution data assimilation (Sun, 2005) at grid lengths in the range from 1 km to 10 km are being used in weather services or are under development across the world. More recent developments have improved both accuracy and extended lead times; see, for instance, Sun *et al*. (2014), who reviewed the progress with the use of NWP in nowcasting, particularly in extending predictions beyond a 1 hour lead time. Kato *et al*. (2017) found that NWP was better than extrapolation for predicting the extent of heavy rainfall, even for lead times less than 1 hour. However, Simonin *et al*. (2017) reported that in the UK, nowcasting using NWP generally did better than other techniques for lead times longer than 2 hours and that it was generally better for the extreme convective rainfall.

In addition to improving on the traditional methods (radar plus NWP), new ideas and techniques are being applied to nowcasting. For instance, Sokol *et al*. (2017) augmented the basic Lagrangian trajectory method of extrapolating radar reflectivity by generating 100-member ensembles of the trajectory from which the probability of precipitation exceeding pre-defined precipitation rates can be calculated. They reported useful lead times up to 60 minutes for low rainfall rates, in the Czech Republic, but a reduction of useful lead time to 30–40 minutes for precipitation rates greater than 3 mm/hour. Shakti *et al*. (2015) added a 30-member ensemble technique to the STEPS method and applied it to nowcasting precipitation amounts in Japan with good results for lead times up to 1 hour. The accuracy of the method was confirmed with radar observations and rain-gauge measurements and was maintained for higher intensity precipitation rates.

In a different approach, Shi *et al*. (2017) realised that the traditional optical flow/Lagrangian advection approach ignores large amounts of historic radar data and they proposed a supervised “deep learning” approach that can learn from historic rain storms. They reported better performance than for the more traditional approach. Han *et al*. (2017) applied a simpler “machine learning” approach and found good predictions of storm movement and growth.

Zollo *et al*. (2015) used both infrared and microwave information from a geostationary satellite with traditional extrapolation methods to nowcast precipitation. They confirmed the usefulness of the method over the Campania region of Italy. However, as might be expected with a more distant data source with greater uncertainty than terrestrial radar, the good performance was generally limited to short lead times of less than 30 minutes.

Several international research programmes addressed the propagation of uncertainty through hydrometeorological forecast systems. For example, the COST Action 717 (Rossa *et al*., 2005) investigated the use of radar observations in hydrological and NWP models by investigating how radar data can be most effectively utilised in model assimilation schemes and in combination with other observations. Additionally, it examined and defined the requirements for European radar data for use in hydrological models. Furthermore, the COST 731 Action (Zappa *et al*., 2010; Rossa *et al*., 2011) considered the application of methods to describe the propagation into hydrological systems of the rainfall uncertainty from NWP models, radar data and nowcasting models through ensembles and how this uncertainty can be communicated to end users (Bruen *et al*., 2010). The COST 731 Action also looked at improvements in NWP applications using radar data assimilation systems to improve short-range QPFs and high-resolution ensemble forecasts (Rossa *et al*., 2010).

In Ireland, the development of a radar rainfall forecasting method and its use for flood forecasting and warning using a radar data stream from Met Éireann was reported by Desta *et al*. (2012). That study and similar recent reports (e.g. Fairman *et al*., 2015) indicate that the Met Éireann radar observations at Shannon and Dublin led to a significant underestimation of precipitation totals, to the point where the radar composite over long periods requires significant adjustment before quantitative use. However, since the publication of these studies, significant refurbishing of the radars has taken place and their current performance may be quite different.

3 Hydrological and Hydraulic Models

3.1 Flood Forecasting Models and Methods

Two different types of water flow models are used in flood forecasting systems. The first type consists of rainfall–runoff (hydrological) models, which provide estimates of river flows or surface water runoff based on rainfall observations and, in some cases, rainfall forecasts. Flow routing models, on the other hand, translate river levels or flows in a channel from one location to others further downstream, sometimes allowing for complicating factors, such as tidal influences and operations at flow control structures. The main types are hydrological and hydraulic (or hydrodynamic) models.

Generally, with these types of models, there is a trade-off between the lead time provided, the forecast accuracy and the uncertainty in outputs. For example, rainfall–runoff models, based on precipitation, can provide longer lead times, but uncertainty in the output is higher than those of flow routing models. For both types, however, whenever possible, forecasts are adjusted based on comparisons with real-time observations. This process, so-called real-time updating or data assimilation, is a key feature; it distinguishes flood forecasting models from their offline simulation counterparts and often leads to improvements in forecast performance. Probabilistic and ensemble techniques (Cloke and Pappenberger, 2009) are also increasingly used to provide an estimate of the uncertainty in model outputs.

3.2 Hydrological Models

The hydrological models may be classified into three main types, viz., conceptual, data-driven and physically based models. These models operate either on a lumped, semi-distributed or fully distributed basis, depending on the type. Simple examples of the use of these models to represent the same catchment are shown in Figure 3.1. Conceptual models represent a river catchment as a series of interconnected conceptual stores, which fill, overflow, drain and empty based on the rainfall inputs and the estimated losses. Typically, various combinations of surface runoff, infiltration, interception, evapotranspiration, soil moisture, percolation and baseflow components are included, using a single "lumped" rainfall input for the whole catchment. Additional sub-models may be further included, such as for reservoirs, the abstractions and discharges related to water supply, and simple flow routing components.

The main data requirements of conceptual models are typically for catchment-averaged rainfall values and potential evaporation (or evapotranspiration) estimates. The sensitivity to the evaporation inputs varies widely between model types and in some cases an assumed seasonal variation may suffice. Where a more accurate estimate is required, Penman and Penman–Monteith approaches may be used. These approaches are based on measurements or estimates of air temperature, wind speed, humidity and radiation. Furthermore, real-time observations of evaporation or evapotranspiration may be used, albeit rarely, on account of difficulties in obtaining reliable estimates.

Data-driven (black box or data-based) models use techniques such as transfer functions and artificial neural networks to represent the translation of rainfall to flows or levels by one or more pathways, but without necessarily requiring a physical interpretation of the underlying mechanisms. For these models, usually, there are fewer preconceptions about the number of parameters, the parameter values or the data inputs required. Nevertheless, sophisticated time series analysis techniques are often needed to identify the optimum data sources, model structure and coefficients. Moreover, in some cases, this process is guided by ideas about the underlying modes and characteristic time scales inherent in the catchment response (Young and Ratto, 2009). Models are usually event based, and therefore a real-time operation requires a suitable starting condition to be provided, such as the current flow or a measure of catchment state.

Physically based models are based on partial differential and other equations for the surface runoff production within grid cells, the drainage to deeper layers and the translation of surface and sub-surface flows between cells. Typically, these make use of

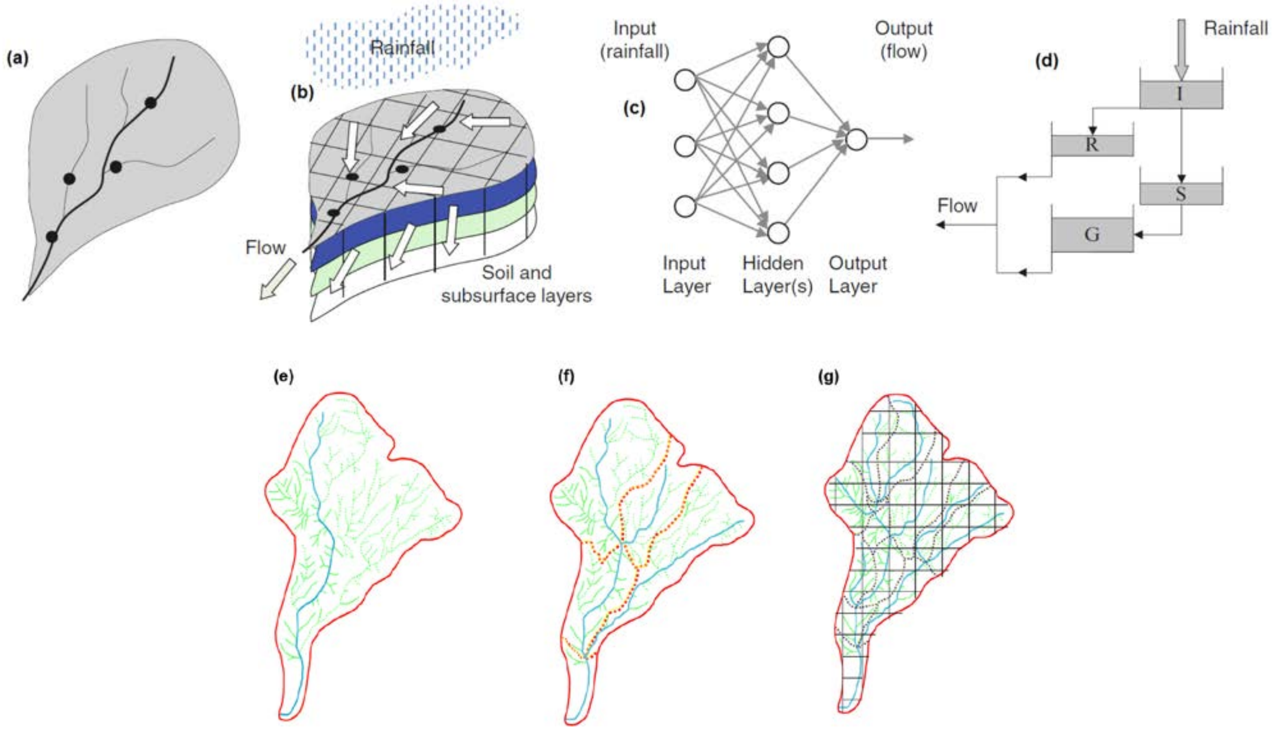

Figure 3.1. Simple model representations of a catchment: (a) plan view of the catchment; (b) physically based model with three soil and subsurface layers; (c) artificial neural network model; (d) conceptual model with interception, surface runoff, soil and groundwater stores; (e) lumped model; (f) semi-distributed model; and (g) fully distributed model. Source: Sene (2008).

grid-based inputs for rainfall and other forcing variables and spatial datasets for land use, topography, river drainage networks and other features. Ideally, the calibration of these models would be based entirely on model parameters derived from laboratory or field experiments. For example, it is sometimes possible to define typical values based on catchment topography, soil types, channel characteristics and other factors. For real-time use, another consideration is that models of this type typically require multiple sources of data at a high spatial resolution. Efficient numerical implementation, as in TOPKAPI (Todini *et al*., 2002), and fast computation performance are important in large spatial domains.

Different combinations of these various approaches may also be employed for flood forecasting. Examples of these include physical-conceptual models, which combine conceptual runoff production and cell-to-cell routing components. Such modelling approaches operate on a gridded basis and data-driven models, which include pathways to represent typical surface and groundwater flow response timescales. The latter are sometimes called hybrid metric-conceptual models or grey box models.

The relative merits of these different modelling approaches have been highly debated (Arduino *et al*., 2005; Todini, 2007; Sivakumar and Berndtsson, 2009; Beven, 2012), and several international intercomparison experiments addressed the issues, specifically for real-time flood forecasting models (WMO, 1992; EFFS, 2003) and more generally for distributed rainfall–runoff models (Reed *et al*., 2004, 2007; Andréassian *et al*., 2006; Smith, M. *et al*., 2013), which provide several useful lessons. Table 3.1 lists some of the advantages of each approach. However, the conclusions regarding specific “brands” of models are often not clear-cut. For example, the results are often influenced by the methodologies adopted (Clarke, 2008), by the data intervals used (e.g. daily or hourly) and by whether or not data assimilation procedures were included in the evaluation.

Some examples of rainfall–runoff models used in operational real-time flood forecasting applications include MIKE SHE (Système Hydrologique Européen) (Refsgaard *et al*., 1995); PDM (the Probability Distributed Model) in the UK (Borga *et al*., 2002; Cole and Moore, 2009; Liguori and Rico-Ramirez, 2013); Grid-to-Grid in the UK (Bell *et al*., 2007;

Table 3.1. Potential advantages of different rainfall–runoff modelling approaches

Model type	Description
Physically based	Well suited to operate with spatially distributed inputs (weather radar, satellite, NWP model outputs, multiple inflow locations, etc.)
	Can represent variations in runoff with both storm direction and distribution over a catchment
	Parameter values are often physically based and can be related to catchment topography, soil types, channel characteristics, etc., including (possibly) the potential to represent events outside the range of calibration data
Conceptual	Fewer parameters to specify or calibrate than in the physically based approach
	Fast and stable for real-time operation
	Easier to implement real-time state updating than for physically based models
Data driven	Parsimonious, run times are fast and models are tolerant to data loss
	Can be optimised directly for the lead times of interest
	The model fitting or data assimilation approach automatically provides a measure of uncertainty for some types of model

Adapted from Sene (2013).

Cole and Moore, 2009); HBV (Hydrologiska Byråns Vattenbalansavdelning) in Sweden (Lindstrom *et al*., 1997), Germany (Ehret *et al*., 2008) and China (Chen *et al*., 2012); TOPMODEL (wide usage; Beven and Freer, 2001) and including Italy (Hossain *et al*., 2004), France (Bonnifait *et al*., 2009) and the Xiangjiang Area in China (Xu *et al*., 2013); HEC-HMS in USA (Neary, 2004); LISFLOOD in Europe (De Roo *et al*., 2000); and URBS in Australia (Malone, 1999), Ireland and South-east Asia (Pengel *et al*., 2008) . For data-driven models, examples include those described by Bárdossy *et al*. (2006), Leedal *et al*. (2013) and Smith, P.J. *et al*. (2013).

The use of physically based models in real-time flood forecasting applications is rare. However, physical-conceptual models have been increasingly adopted, particularly to provide flood alerts for ungauged catchments and/or longer range ensemble forecasts at a regional or national scale (Vehviläinen *et al*., 2004; Cole and Moore, 2009; Thielen *et al*., 2009; Javelle *et al*., 2014). The lead times and spatial scales considered vary widely.

3.3 Flow Routing Models

The main approaches to flow routing in flood forecasting include hydrological and hydrodynamic routing models (Figure 3.2). Hydrological routing models typically conserve the water balance in a river reach, using approximations to the full equations of motion or more empirical formulations. Examples include the kinematic wave and Muskingum–Cunge approaches (Lighthill and Whitham, 1955; Cunge, 1969). Hydrodynamic models, on the other hand, solve either one-dimensional, two-dimensional or three-dimensional approximations to the Navier–Stokes equations of fluid motion. For river modelling applications, the depth-averaged solutions of the shallow water Saint Venant equations are widely used (Chanson, 2004).

For a simple river reach with no complications, the main effects that need to be captured typically include the time delay and attenuation of the flood wave as it passes down the channel as well as any significant inflows or outflows (e.g. from tributaries or abstractions). Hydrological flow routing models often provide reasonable results for this type of situation and are both simpler to calibrate and faster to run than hydrodynamic models. Furthermore, river channel and floodplain surveys are usually not required, although some commercially available packages provide the option to estimate key parameters, such as wave speed and attenuation coefficients, using indicative channel cross sections.

In contrast, hydrodynamic models are usually considerably more time-consuming to build and calibrate. Nevertheless, they are better able to represent factors such as tidal influences, operations at flow control structures and floodplain flows. Normally, a river channel survey is required and digital elevation models are widely used for the floodplain geometry.

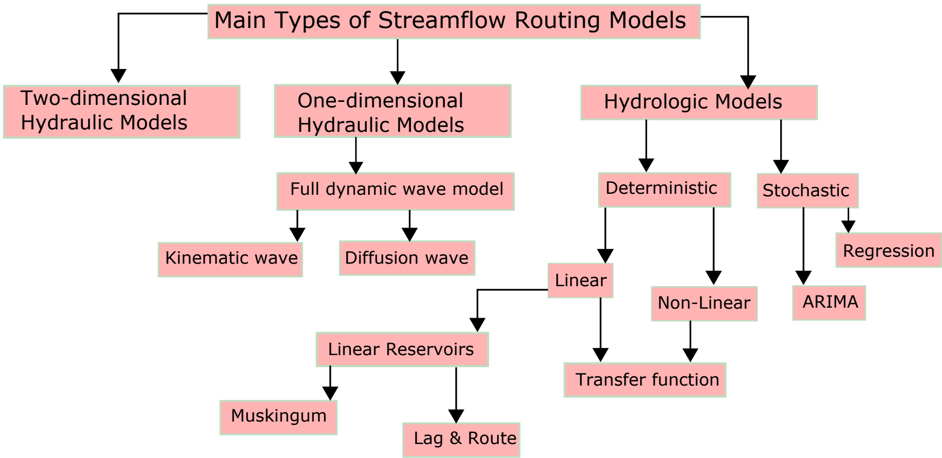

Figure 3.2. Classification of streamflow routing models.

For flood inundation modelling, a classification of models is shown in Table 3.2.

These approaches (Table 3.2) represent river channel and floodplain flows in increasing amounts of detail. A common choice for flood risk mapping is a combined 1D/2D approach (e.g. ISIS – now FloodModeller Pro – and LISFLOOD-FP) for the river channel and floodplain. However, although it is difficult to generalise, the model run times required often increase as the model complexity increases.

Table 3.2. Classification of floodplain inundation modelling approaches

Model dimension	Model description	Some available software	Potential applications
0D	No physical laws included in simulations	ArcGIS, Delta mapper, etc.	Broad-scale assessment of flood extents and flood depths
1D	Solution of the one-dimensional Saint Venant equation	Infoworks RS (ISIS[a]), Mike 11, HEC-RAS	Design scale modelling that can be of the order of tens to hundreds of km depending on catchment size
1D^{+}	1D plus a storage cell approach to the simulation of floodplain flow	Infoworks RS (ISIS[a]), Mike 11, HEC-RAS	Design scale modelling that can be of the order of tens to hundreds of km depending on catchment size and which also has the potential for broad-scale application if used with sparse cross-sectional data
2D^{-}	2D minus the law of conservation of momentum for the floodplain flow	LISFLOOD-FP	Broad-scale modelling or urban inundation depending on cell dimensions
2D	Solution of the two-dimensional shallow wave equations	TUFLOW, Mike 21, TELEMAC, DIVAST	Design-scale modelling of the order of tens of km. May have the potential for use in broad-scale modelling if applied with very course grids
2D^{+}	2D plus a solution for vertical velocities using continuity only	TELEMAC 3D	Predominantly coastal modelling applications where three-dimensional velocity profiles are important. Has also been applied to reach-scale river modelling problems in research projects
3D	Solution of the three-dimensional Reynolds-averaged Navier–Stokes equations	CFX, FLUENT, PHEONIX	Local predictions of three-dimensional velocity fields in main channels and floodplains

Source: Pender (2006).

[a]Now replaced by Flood Modeller Pro, CH2M's next-generation flood modelling software.

Consequently, most real-time applications use *1D* or *1D⁺* approaches. However, the use of *2D* approaches is beginning to gain popularity for modelling the surface water component in urban flood forecasting applications. Moreover, improvements in computer processors and algorithms are increasingly making this approach feasible for flood forecasting applications.

3.4 Selection of the Appropriate Model for Flood Forecasting

The main factor affecting the choice of a method or model for flood forecasting is understanding and correctly defining the purposes for which the method or the model will be used. The availability of data strongly influences the selection of the type of modelling approach and the spatial scale and coverage required (Kauffeldt *et al*., 2016). For example, at one time, the Environment Agency in England relies on over 1400 different models for the national flood forecasting service (Liam Gaffney, Technical Advisor at the Environment Agency, 2016, personal communication). For real-time flood forecasting, the following additional factors must be considered when selecting a model (WMO, 2013):

1. forecasting lead time versus time of concentration/travel time in the river reach;
2. robustness in dealing with instabilities or large forecasting errors even if slightly less accurate approaches are adopted;
3. computational time to ensure that the forecast is available in time for the flood managers and dependent responders to guarantee effective decisions, which, in practice, discourages using sophisticated and accurate approaches that are nevertheless time consuming.

The main project report provides detailed descriptions of the common models used in operational flood forecasting systems that may be useful for applications in Ireland.

4 Operational Flood Forecasting Systems

4.1 Forecasting Systems

Flood forecasting models are normally operated within a flood forecasting system (Figure 4.1). The advantages of adopting this approach typically include the automation of routine tasks, maintenance of audit trails during flooding events and production of a wider range of outputs than would otherwise be possible.

Typically, a forecasting system manages the processes of data gathering, initial data validation, scheduling of model runs and post-processing of model outputs. Most systems also include a telemetry polling component with alarm handling and flood warning dissemination components. The number of inputs required can be large. Examples include river, reservoir, lake and tidal levels, control structure settings, rain gauge, weather station and weather radar observations, and meteorological forecasts of various types.

Table 4.1 illustrates some of the functionalities typically available in modern flood forecasting systems. Many flood forecasting centres operate systems of this type, either developed "in-house" or using commercially available products. Some examples include Delft-FEWS, MIKE FLOOD watch and FloodWorks (now ICMLive). Normally, a user-friendly, map-based interface is provided, with the options to view and compare forecasts using graphical, tabulated and other types of output. Model configuration, calibration and validation tools are sometimes included. Open-architecture systems (e.g. Delft-FEWS) are increasingly used (e.g. UK National Flood Forecasting Service), which are open in the sense that any model that meets certain standards can be included in the system.

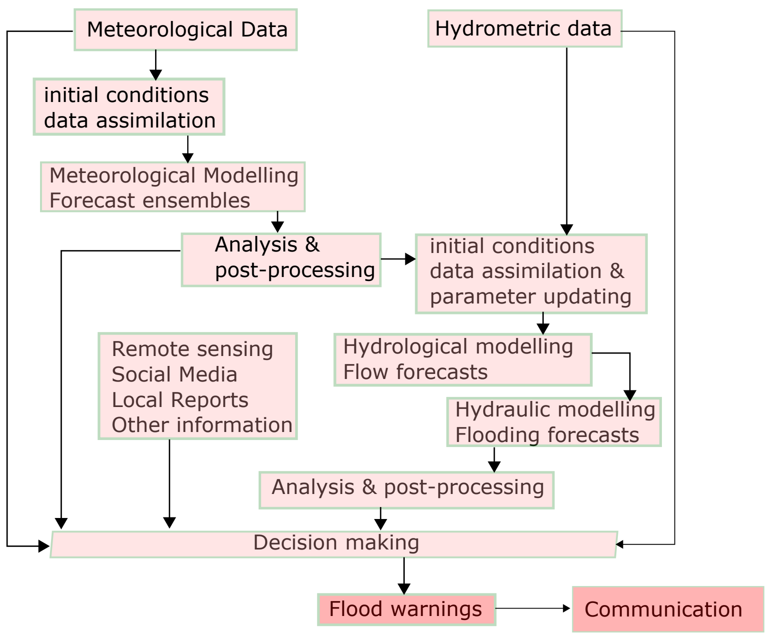

Figure 4.1. Possible linkages between meteorological and flood forecasting systems.

Table 4.1. Typical functionality in flood forecasting systems

Item	Function	Description
Pre-processing	Data gathering	Polling of instruments directly, or receiving data from a separate telemetry system (see data interfacing)
	Data interfacing	Interfacing to a range of real-time data feeds and forecast products from various sources (meteorological, river, coastal), possibly also including grid-based or catchment-averaged weather radar data and meteorological forecasts, and possibly ensemble inputs (e.g. rainfall forecasts)
	Data validation	Real-time validation using a range of time series, statistical, spatial and other validation methods
	Data transformation	Transformation of input data into the values required by the modelling system (e.g. catchment rainfall estimates), including infilling missing values by interpolation, regression and other methods
Model runs	Model run control	Scheduling and control of model runs, including ensemble forecast runs, model initialisation, error handling and operation of simpler back-up forecasting models (if available), including automatically initiating model runs for longer periods if there has been a gap in operations
	Data assimilation	Application of real-time updating and data assimilation algorithms, with comparisons of original and updated forecasts, and possibly allowing forecasters to manually adjust forecasts
	Data hierarchy	Automatic fallback to alternative options in case of failure of one or more inputs
Post-processing	Model outputs	Processing of model outputs into reports, maps, graphs, web pages, etc., and for onward transmission to decision support systems and end users (as required)
	Inundation mapping	Intersection of inundation extents with street and property databases to generate maps and lists of properties at risk
	Alarm handling	Raising alarms when thresholds are forecast to be exceeded, using map-based displays, email, text messaging, etc.
	Data storage	Maintaining an archive of all input data, forecasting model run outputs and other key information
	Performance monitoring	Automated calculation and reporting of information on model performance and system availability
	Audit trail	Maintenance of a record of data inputs, model-run control settings, model forecast outputs, operator identities, etc.
	Replay	The facility to replay model runs for post-event analysis, operator training and emergency response exercises
User interface	General	Map-based, graphical and other displays of input data, forecast outputs, alarms, etc., including overlays of aerial and satellite photography
	What if functionality	The option to run scenarios for future rainfall, flood defence breaches, gate operations, dam breaks, etc.
	System configuration	Interactive tools for offline configuration of models, data inputs, output settings, alarms, etc., and to define user permissions and passwords (e.g. view, edit, administrator)
	Model calibration	Offline tools for calibration of models

Adapted from Sene (2013).

4.1.1 MIKE OPERATIONS (formerly FloodWatch)

MIKE OPERATIONS has succeeded MIKE FloodWatch; it is a decision support system for real-time forecasting that integrates data management, monitoring, forecast modelling tools and dissemination methodologies in a single, user-friendly ESRI ArcMap GIS environment. Operationally, it can run automatically using a built-in task scheduler, manually when the operator controls the system or as a combination of both. Moreover, it can be customised using built-in scripting facilities. The system can be used to manage and examine data imported in real time from a range of external sources, including point observations and grid-based data from weather models and radar and satellite imagery.

Telemetry data is imported from hydrometeorological networks through the data import and conversion module, which can be run automatically or manually. Quantitative forecasts of precipitation and temperature during the forecasting period can also be imported automatically or manually. The first step before a forecast simulation is to process the input data. Users can specify quality control procedures for each data stream and link to common commercial database engines. Once a request for a forecast is made (either manually or automatically) the system will extract the required data from the FloodWatch database and convert to the MIKE 11 format. The model simulation is then automatically executed and the MIKE 11 simulated forecasts (water levels and flows) are transferred back to the FloodWatch database for output (display and dissemination).

4.1.2 Delft-FEWS

The framework of Delft-FEWS (Werner and Heynert, 2006; Werner *et al*., 2013) provides a platform through which operational forecasting systems can be constructed. It allows flexibility in the integration of models and data. Unlike many modular-based flood forecasting systems, the Delft-FEWS system contains no inherent hydrological modelling capabilities within its code base. Instead, it relies entirely on the integration of (third-party) modelling components. The intent is to provide a data-centric shell through which operational forecasting applications are developed, specific to the requirements of an operational forecasting centre. Delft-FEWS evolved around a data-centric approach, with a common data-model through which all components interact.

In an operational environment, large volumes of dynamic time series data are employed. This volume is rapidly increasing, particularly with the emergence of high-resolution NWP (De Roo *et al*., 2003), remotely sensed data products (Weerts *et al*., 2011) and distributed models used in operational forecasting.

The approach taken to integrating models is to run these as an external process. Delft-FEWS provides the required input data and parameters, executes the model and reads the results. Over 50 model codes from a broad range of model developers and suppliers have been integrated to run from Delft-FEWS, including most of the models presented listed in this report. DELFT-FEWS is used throughout the world in many different countries.

4.1.3 FloodWorks (now ICMLive)

The system, originally called FloodWorks and now called ICMLive, integrates data assimilation, hydrological and hydrodynamic modelling, analysis, alarm notification, decision support and control within a user-friendly, automated, real-time environment. The software is modular and operates either on single personal computers (PCs) for single user applications or can be distributed over multiple PCs connected across both LANs and WANs for wider implementations.

A network of models calculates forecasts of flow, level and other variables at distinct “forecast points” throughout a river basin or urban catchment. Many types of models, including hydrological and hydrodynamic, can be combined into a single, integrated network. The outputs from each model can be combined with observed data in order to update the models’ forecasts, which in turn provide the input to models further downstream. Forecasts are “hot-started” from previous runs and involve only the minimum necessary computation.

The package can access a library of model algorithms, ranging from the simplest algorithm for filling in gaps in time series through to hydrological process algorithms for rainfall–runoff modelling and flow routing, and the highly functional InfoWorks RS, SD and CS hydrodynamic algorithms.

4.2 Operational Forecasting Systems Available in Ireland

4.2.1 Munster Blackwater Mallow – Initial Flood Forecasting System

This is a fluvial forecasting system and was developed in phases. The Initial Flood Forecasting System (IFFS) produced forecasts throughout the catchment and currently provides forecasts for the towns of Mallow and Fermoy. It is based on river level gauges upstream of Mallow and Fermoy. River level data are obtained from the gauges by telemetry and the forecasting is undertaken by Cork County Council using an OPW-developed spreadsheet (which has now been incorporated into the PFFS, described in section 4.2.2). Prior to the development of the Preferred Flood Forecasting System (PFFS), the primary purpose of the IFFS was to provide a trigger for the timely erection of demountable defences in Mallow. It now provides a backup to the PFFS.

4.2.2 Munster Blackwater Mallow – Preferred Flood Forecasting System

A new forecast system called the Preferred Flood Forecasting System (PFFS) was produced for Mallow and Fermoy. The system is based on a Unified River Basin Simulator (URBS) model, which is a hydrological model based on rainfall–runoff and runoff routing. URBS was first developed in Australia and used operationally in 1992. Data for the URBS model are provided by a telemetered river and rain gauge network, and the forecasting system is operated through the FloodWorks Management System (produced by Innovyze) by Cork County Council. The system is currently operational but is still undergoing continual improvements. As with the initial system, the primary purpose of the system is to enable the erection of demountable barriers when necessary. The preferred system provides the additional benefit of delivering more accurate forecasts than the initial spreadsheet system, providing forecasts of both river level and flow, with established longer warning times for specific locations.

4.2.3 Suir FFS Clonmel – Preferred Flood Forecasting System

An initial flood forecasting system for Clonmel was implemented in a spreadsheet, but the current system developed by the OPW for the Suir is based on the URBS rainfall–runoff model, which is run in parallel with the earlier spreadsheet system. It covers the Suir catchment to Clonmel, but could be extended to cover other towns in the future. It delivers more accurate forecasts than the initial system alone. It provides forecasts of both river level and flow, with established warning times for specific locations.

4.2.4 Bandon Flood Early Warning System

The Bandon Flood Early Warning System (BFEWS) became operational in December 2010. The system was developed by Cork County Council, with financial support from the OPW, Bandon Town Council and local businesses. Technical assistance was provided by the OPW. Cork County Council employed RPS Consulting Engineers to design the system. The system alerts local authority staff and members of the public of a potential flood event based on water level data at upstream locations along the Bandon River. Eligible members of the public may register online to receive alerts by text message. The BFEWS website, www.bandonfloodwarning.ie, displays the real-time flood warning status based on the following four flood warning threshold levels:

1. all clear – no flooding (emergency code: green);
2. minor flooding (emergency code: yellow – low/ high);
3. serious flooding (emergency code: orange);
4. severe/major flooding (emergency code: red).

4.2.5 ESB Shannon Lakes water level forecasting system

The ESB has developed a flood forecasting model for the River Shannon, which predicts levels in and discharges from three major lakes (Lough Allen, Lough Ree and Lough Derg). The system became operational in 1986. The model was developed at that time in order to determine design floods in Lough Allen and Lough Derg for dam safety purposes. It is only in recent years that the model has been tailored to become a predictive tool. Two forecasts are run weekly during periods of high flows/levels. Predictions are issued by email to all relevant stakeholders on the Shannon, such as local authorities, Waterways Ireland, OPW and the Irish Farmers' Association (IFA).

4.3 Operational Forecasting Systems in Other Countries

4.3.1 European Flood Awareness System

The European Flood Awareness System (EFAS) is an initiative of the European Commission (EC) developed by the Joint Research Centre (JRC) to increase preparedness for riverine floods across Europe. It has been operational since 2012. After the devastating, widespread flooding on the Elbe and Danube rivers in 2002, the EC began development of EFAS, with the aim of providing transnational, harmonised early warnings of flood events and hydrological information to national agencies, complementing local services (Thielen *et al.*, 2009).

The European Flood Awareness System uses four different meteorological NWP forecasts as input, two ensemble forecasts and two deterministic from three different providers: ECMWF, the Deutscher Wetterdienst (DWD) and the Consortium for Small-scale Modelling (COSMO). The precipitation, temperature and evaporation from each of the four forecasts are used as input to the LISFLOOD hydrological model, which is used as both the rainfall–runoff and the routing components of EFAS. LISFLOOD simulates canopy, surface and sub-surface processes, such as snowmelt (including accounting for accelerated snowmelt during rainfall) and preferential (macropore) flow, soil and groundwater processes (Thielen *et al*., 2009).

The simulated ensemble hydrographs produced by LISFLOOD do not constitute a flood forecast by themselves. A decision-making element, based on thresholds, is required (Thielen *et al*., 2009). On account of the limited number of discharge observations in many areas of the globe, these critical thresholds cannot yet be derived directly from observations. Meteorological data are run through LISFLOOD to calculate 20-year time series of discharge, from which reference thresholds for minor or major flooding are estimated at each grid cell.

Alongside warnings for each forecast point, the EFAS interface (e.g. Figure 4.2) provides ensemble hydrographs, which allow the interpretation of the spread of the ensemble and the uncertainty in the forecast. Persistence diagrams showing information about the previous four forecasts also give the user additional information on the forecast uncertainty, as NWP models should be able to pick up large-scale synoptic weather systems that typically produce severe events in advance, therefore showing a flood risk consistently in each forecast run (Thielen *et al*., 2009).

The EFAS complements existing national flood-forecasting tools, since it forecasts flooding in transboundary catchments across Europe in one system. The main purpose of EFAS is to deliver early probabilistic warnings rather than very detailed forecasts that one would be able to get from a national forecasting system.

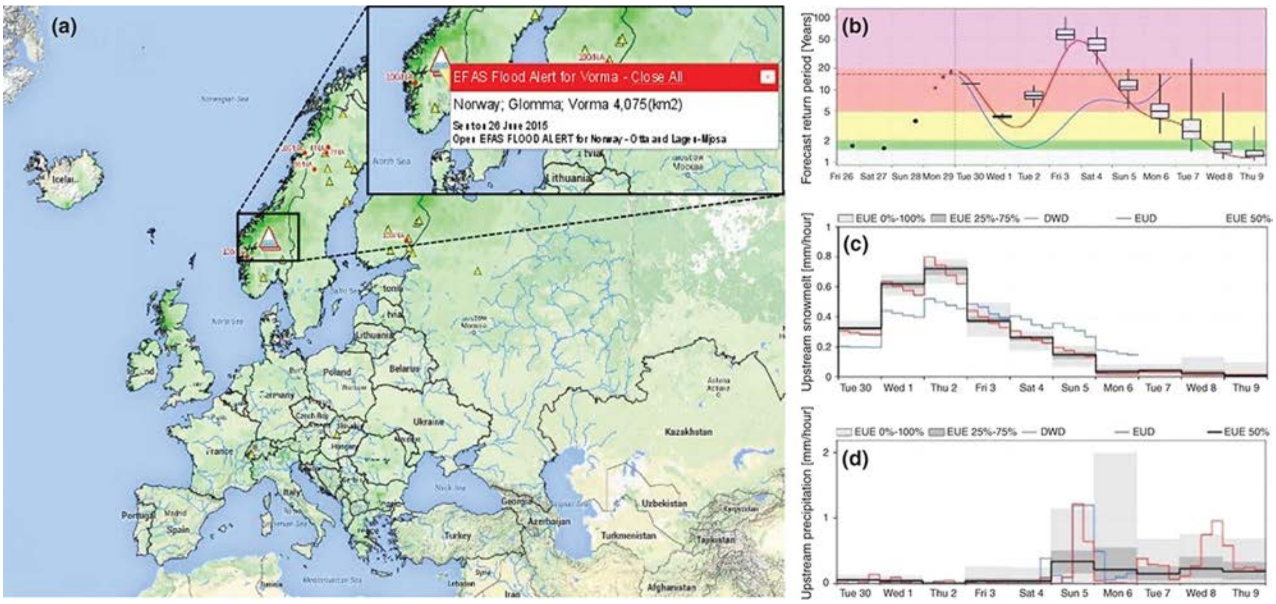

Figure 4.2. EFAS showing (a) the main interface with high (red) and medium (yellow) reporting points, flood alerts (warning triangles) and probability (% likelihood) of exceeding 50 mm of precipitation (green shading) during the forecast period (10 days); (inset a) the flood alert displayed when the alert point is clicked on; (b) the return period hydrograph with return period thresholds (1.5 years, green; 2 years, yellow; 5 years, red; 20 years, purple); (c) upstream snow melt forecast; and (d) upstream precipitation forecast.

4.3.2 US Hydrologic Ensemble Forecast System (HEFS)

In the USA, Hydrological Ensemble Forecast System (HEFS) is run by the National Weather Service (NWS) and, for river basins across the USA, provides “uncertainty-quantified forecast and verification products” (Figure 4.3; Demargne *et al*., 2014). It has been implemented to run as part of each river forecasting centre’s (RFC) configuration of the FEWS-based Community Hydrologic Prediction System (CHPS). CHPS is an open service-oriented architecture built on the Delft-FEWS framework (Werner *et al*., 2013) and has been the software platform used to run the traditional deterministic flood forecasts and long-range ESP forecasts since 2010.

The output of HEFS uses ensemble hydrographs (see Figure 4.4) to produce visualisations of the forecasts that can be communicated to a range of end users for decision making and warning dissemination. These final forecast products include spaghetti plots, exceedance probabilities in the form of bar graphs and probability distribution plots, using comparisons

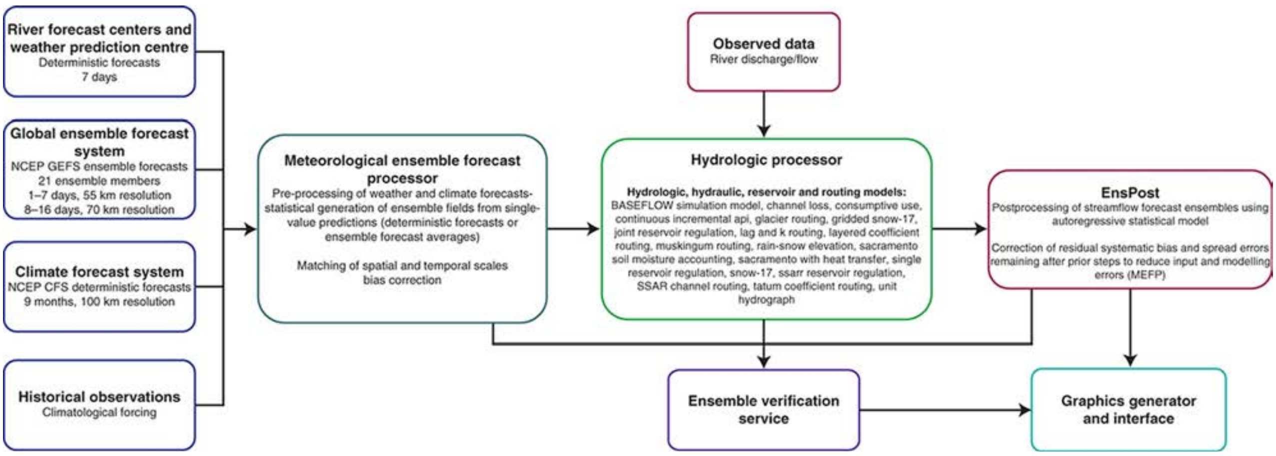

Figure 4.3. Components of the US HEFS. Source: Demargne *et al*. (2014).

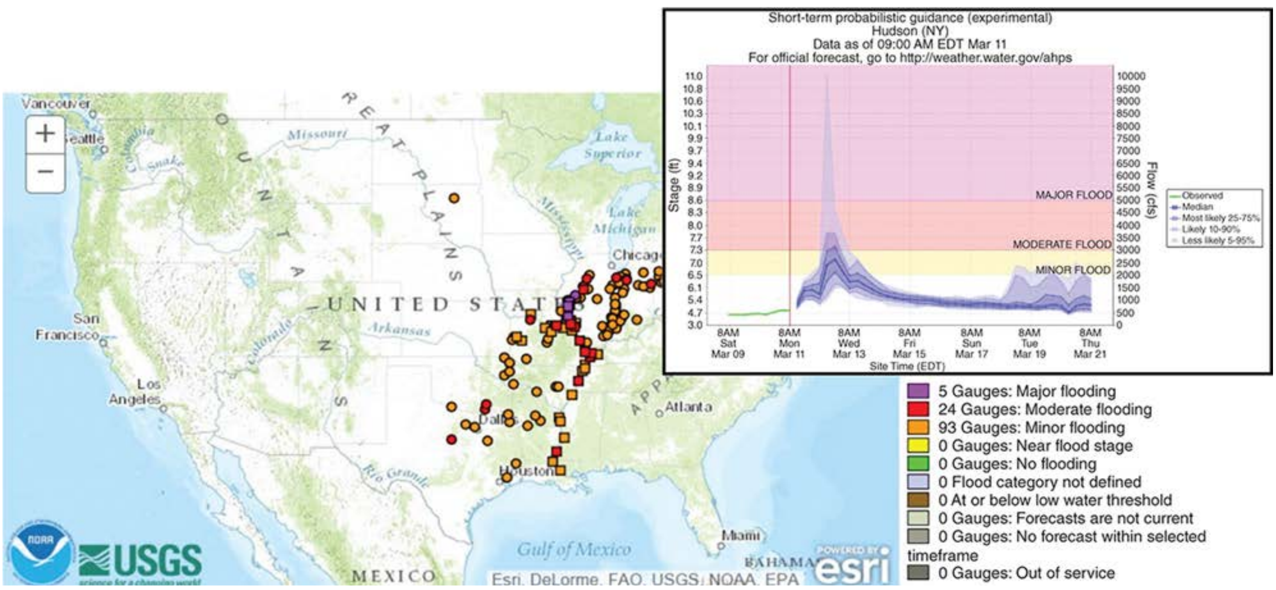

Figure 4.4. Overview map of the US HEFS showing flood forecasting locations. An ensemble hydrograph is shown for a flood event at one river location, including observed stage and flow (green), forecast stage and flow (purple) in terms of probabilities, and colours indicating the forecast severity based on flood stage data (minor flood, yellow; moderate flood, red; major flood, pink). Forecasts are available at water.weather.gov/ahps/forecasts.php

with historical simulations (reanalysis datasets), and an expected value chart describing the ensemble distribution

4.3.3 Global Flood Awareness System

Global Flood Awareness System (GloFAS) uses surface and sub-surface runoff forecasts produced by an NWP model to produce probabilistic flood forecasts with up to 2 weeks lead time and has been used in a pre-operational environment since 2011 (Alfieri *et al.*, 2013). It provides early warnings and information on upstream river conditions alongside global overviews of upcoming flood events in large river basins for decision makers ranging from water authorities and hydropower companies to civil protection and international humanitarian aid organisations (Figure 4.5). ECMWF and JRC do not directly disseminate these flood warnings, as each country has national procedures to follow; however, each country is able to access and analyse the forecasts for decision-making purposes and research.

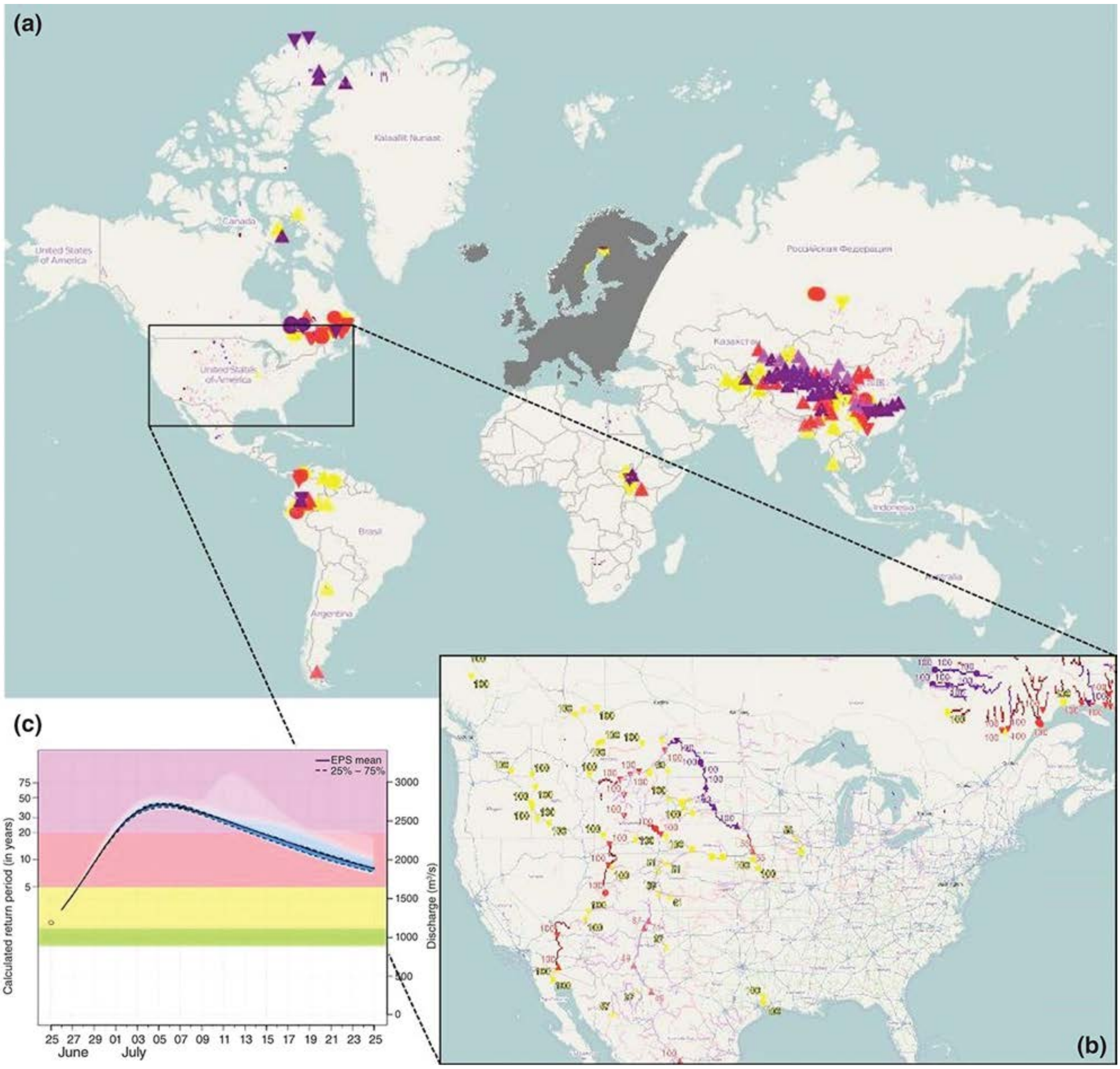

Figure 4.5. GloFaS interface showing (a) a global overview of medium (yellow), high (red) and severe (purple) reporting points; (b) a more detailed view of warning points in the USA; and (c) the return period hydrograph with return period thresholds (1.5 years, green; 2 years, yellow; 5 years, red; 20 years, purple) for one point in the USA. Forecasts are available at www.globalfloods.eu.

4.3.4 Po River basin hydrological forecasting in Piedmont

The Po and Ticino Rivers have short concentration times and both are susceptible to flash flooding, so the area downstream of their confluence has a high flood risk. A hydrological forecasting system was developed to facilitate better management of the rivers. It models the entire Po catchment to its confluence with the Ticino River with a real-time forecasting system using a hydrological simulation approach. It uses several modules of the one-dimensional computational software MIKE 11 produced by the Danish Hydraulic Institute (DHI). The meteorological input to the system is supplied daily by the Italian Regional Agency for the Protection of the Environment (ARPA Piemonte) meteo forecasting office. Other observation data come from the regional meteohydrological monitoring network. While the system is configured to operate automatically, the ARPA technicians can also manage the system based on specific needs, simulating alternative scenarios.

4.3.5 Australian Flood Forecasting and Warning System

The Australian Bureau of Meteorology (BoM) generates short-term (up to 7 days ahead) continuous streamflow forecasts using deterministic NWP models within its Hydrological Forecasting System (HyFS). The system is based on the Delft-FEWS forecasting framework (Werner *et al*., 2013) alongside event-based hydrological modelling and nowcasting using radar rainfall estimates. The BoM services also rely on forecasters for the dissemination and communication of flood warnings and local information on expected river conditions. The NWP forecasts used to force the rainfall–runoff models are produced by the BoM's Australian Community Climate and Earth-System Simulator (ACCESS) NWP model.

It uses the semi-distributed GR (Génie Rural á 4 Paramètres) hydrological model, and event-based forecasting is also used extensively. The resulting river discharge estimations from both model versions are used, alongside observed data and statistical models, to produce automated graphical products, such as maps, bulletins, warnings and alerts.

5 FloodWarnTech Workshop

5.1 Introduction

The FloodWarnTech project organised a 1-day workshop of “Flood Warning Technologies”, which took place on 19 January 2016 in the Newstead Building of University College Dublin. The purpose of the workshop was to:

1. describe some of the internationally available flood warning platforms, suitable for use in Ireland; and
2. provide an opportunity to discuss their warning requirements with potential users of warning systems and with stakeholders who may use their outputs.

There were two international speakers, Dr Jan Verkade from Deltares in the Netherlands and Dr Mark Bailes from the DHI Group in Denmark, and two Irish keynote speakers, Mr Timothy Joyce and Mr Mark Hayes, both from OPW. In addition, there were invited presentations from Mr Colm Brennan and Mr Gerald Murphy (Cork County Council), who described their experiences of flooding and warnings systems.

Two breakout sessions took place, one in the morning session and one in the afternoon, at which the participants’ views and opinions were surveyed in small group discussions. Each participant was assigned to a group (with 7 or 8 persons per group) and was asked to discuss a pre-set number of issues and to write their ideas and opinions on cards. Each group appointed a rapporteur. After the session, each rapporteur gave a short summary of the topics discussed and opinions expressed in their group. This was recorded to facilitate the production of an accurate record. The handwritten cards produced by each group were collected and these also contributed to the record of the session. The topics for each session were as follows.

- **Breakout session 1: Morning – Technical Requirements**. What are the technical requirements for a useful flood warning system in Ireland?
- **Breakout session 2: Afternoon – Forecast Uncertainty → Decision → Response**. How might information about forecast uncertainty be used in making flood management decisions and in eliciting response? It is now possible to have forecast uncertainty information. Should, and if so how, can this information be used by decision makers? How should it be presented and what other information is required to guide the response to floods?

5.2 Conclusions and Summary of Results

Details of the individual points raised at the breakout sessions are given in the full main report and are summarised below. The conclusions from the breakout sessions were as follows.

1. More data are needed (including for smaller catchments); higher temporal and spatial resolution; evapotranspiration, radar, groundwater, integrated “Big-data” management); any data ownership issues should be resolved; resilience and maintenance (including funding for equipment and staff) of measuring networks should be considered; quality assurance should be an integral part of data management; CFRAM database needs to be adopted.
2. There is a need to have social and community involvement, tailor warnings to specific target groups, set realistic expectations, have standard technical guidance for reporting, educate the public on flood risks and improve awareness.
3. More media involvement is needed in the dissemination of warnings, information and instructions for planning responses.
4. Improvements in modelling should be sought, for example, how best to present alerts and uncertainty information to decision makers and the general public, and whether or not to use return period or probabilities. It is important to take account of antecedent soil moisture conditions in models. The group queried whether or not full automation is possible in warning systems. Progressive development and user

training is needed. Post-event analysis of system performance should be undertaken after major events (or major false alarms).

5. Maintenance of rivers was cited as an issue that can change flood risk in specific locations.
6. More detailed flood response planning is required at the appropriate scales.

6 Report on Potential of Radar and NWP as Sources of Precipitation Information for Flood Forecasting

6.1 Introduction

The FloodWarnTech project examined the precipitation data resources (measurements and forecasts) available in Ireland, as these are key requirements for an operational flood forecasting system. The value of the different sources of precipitation was assessed. Such data came from direct measurements on the ground (rain gauges), indirect observations in the air (radar) and predictions from atmospheric models (NWP). All three sources of information were tested in three catchments, using historic data, and their performances were assessed by comparisons with measured river flows, as described in detail below.

6.2 Data Sources

6.2.1 Precipitation

All the precipitation information was provided by Met Éireann. Three different types of measurement were used:

1. Rain-gauge measurements (daily or hourly).
2. Radar estimates of rainfall (every 15 minutes).
3. NWP reanalysis. Met Éireann is currently in the process of using a regional Numerical Atmospheric Model to reanalyse historical weather data and produce corresponding estimates of weather fields throughout Ireland on an approximate 1 km grid. At the time of the study (2016/2017), these data were not yet officially released. However, preliminary outputs for a 3-year period (2001–2003) were made available to the project by Dr Ray McGrath and are used here. Thus, the project tests only covered this period to enable direct comparisons of the performances of rain gauges, radar and NWP (reanalysis).

6.2.2 Potential evaporation

Potential evaporation is estimated at Met Éireann synoptic stations. None of these was located within the study catchments, so, for each catchment, the data from the nearest stations are used here.

6.2.3 Discharge

The OPW and the Environmental Protection Agency (EPA) collect and archive water level and flow data for most major Irish rivers and lakes and these data are used here.

6.3 Catchments

Three catchments, of varying size, were used to test the river modelling and flow forecasting software:

1. Dodder at Waldron’s Bridge (area: 94.26 km^2);
2. Boyne at Slane Castle (area: 2408 km^2);
3. Suir at Cahir Park (area: 1602 km^2).

6.4 Dodder

The Dodder rises in a steep mountainous area near Kippure peak in the Dublin mountains at an elevation of 754 metres above Ordnance Datum (m.a.O.D.). It is 27 km in length and drains a catchment area (to the sea) of 113 km^2. Although it starts with a steep gradient, it eventually flows through a flat urban area before entering the sea near Irishtown in Dublin City. Its steep mountainous upper part consists of deep blanket bog overlying granite, areas of metamorphic and Silurian formations and possible deposits of sand and gravel. Two major reservoirs have been built on the river at Castlekelly. The main channel bypasses the upper reservoir in a canal, except under flood conditions, when the excess enters the reservoir over a side weir. That canal feeds the smaller, lower reservoir, referred to as the Miller’s Pond, which discharges over a spillway back into the original river channel. Currently, the main purpose of those reservoirs is to supply water for the Dublin area, but they could provide the possibility of some flood control if proper warning and management systems were developed. The Dodder has four major tributaries: the

Owendoher, Little Dargle, Dundrum Rivers and the Tallaght Stream. It flows through some areas of glacial deposits of gravel and boulder clay.

During the construction of the reservoirs, between 1885 and 1886, rainstorms of 96.5 mm and 93.5 mm were recorded over a period of 19 hours. One of the most significant storms of the 20th century occurred in 1905, when rainfall of more than 200 mm was measured, and the spillway of the lower reservoir was overtopped by 1.22 m. Another significant storm, in 1986, was tropical storm (Hurricane) Charley, which delivered rainfall estimated at 190 mm over 24 hours, and a depth of 0.91 m was recorded on the spillway. Other major floods occurred in 1891 and 1931. Because it rises in the Dublin mountains, the Dodder has a quick response to precipitation and as it then flows through an urban area, the resulting floods can cause extensive damage. Extreme flooding was recorded in 1787, 1794, 1802, 1807, 1851, 1905, 1931, 1958, 1965 and 1986. As an example of this, on 25 and 26 August 1986, Hurricane Charley flooded a total of 465 properties, some with up to 2.5 m of water, and the economic loss exceeded the modern-day equivalent of 7.5 million euro, including in a number of neighbouring catchments because of the large number of commercial premises subjected to flooding. Both the Dodder and sister river Dargle, which drains the east side of the Dublin mountains, and flows through Bray, burst their banks. Total insurance claims for both rivers reached 32 million euro. Following Hurricane Charley, Dublin City Council carried out a re-evaluation of the quantum of the probable maximum flood and its impact on the two earth embankment dams at Bohernabreena. This resulted in the construction of wave walls on both dams to prevent overtopping and the construction of a major overflow spillway and bypass channel to limit any risk of the dams being overtopped in extreme flood conditions.

Eleven of the weirs along the lower reaches stream (excluding those at the outlet of the lower reservoir), have been used in the past to provide water for power generation. Following serious flooding in the Irishtown area in 2003, mainly due to a combination of high tides and coastal surge, flood protection walls were constructed on the lower Dodder. More recently, improvements in the channel were provided up to and beyond Ballsbridge.

6.4.1 Data for the Dodder catchment

The rainfall data were provided by Met Éireann. There are a total of 11 rain gauges still operating, within or close to the Dodder catchment, with varying lengths of record. Of these five are reliable: three in the Glenasmole area, one at Rathfarnham Castle and one in Ballsbridge, but the other two were closed before the period of data used in this study (2001–2003). Most of the stations collect daily rainfall data totalling from 9 a.m. to 9 a.m. the following morning and taking the total as applying to the previous day. However, continuous chart records are available for Casement Aerodrome (outside the catchment) and Glenasmole DCWW. The rainfall stations used in this report are marked with numbered solid green disks in Figure 6.1.

While 21 rain gauges are listed in the Met Éireann database to be in or close to the Dodder catchment, only five of these were recording in the period 2001–2003 (Figure 6.1), as many had closed prior to this. All recorded daily precipitation only. The closest station recording at sub-daily time steps (e.g. hourly or less) in the period 2001–2003 was Casement Aerodrome, also shown in Figure 6.1. Because of the small size, steep slope and rapid response to rainfall, a daily time step is inadequate for modelling. Here we used an hourly time step, by scaling the hourly temporal distribution of rain at Casement Aerodrome to match the magnitudes of the rain recorded at the gauges within the catchment. The factors ranged from less than 1 (for the Simmonscourt gauge) to nearly 1.7 for one of the gauges in Glenasmole.

Twenty-three NWP data grid points lie in or near the Dodder catchment (Figure 6.2). An hourly NWP time series for the period 2001–2003 was produced by averaging these. Radar precipitation information, from the Dublin airport radar, is available on a 1 km grid. The intersection of this grid with the Dodder catchment is shown in Figure 6.3. For each of these grid squares, 15-minute rainfall estimates of precipitation were abstracted and summed to give hourly values for the entire catchment for the period 2001–2003. The discharge data used here are hourly values of flow at the EPA gauge at Waldron's Bridge. The potential evaporation data are daily values for Casement Aerodrome, distributed over a 12-hour (day) period and assumed zero for the remaining 12-hour (night) period.

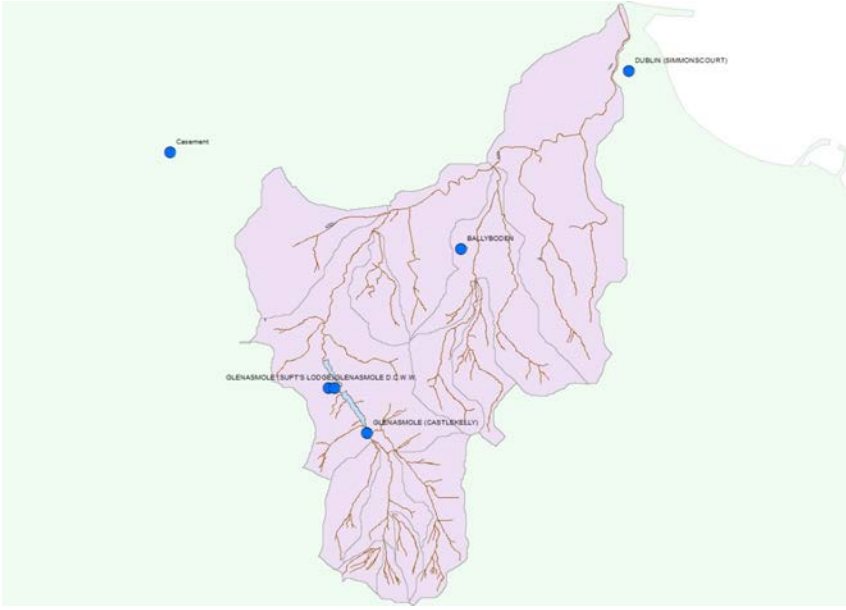

Figure 6.1. Locations of rain gauges in or near the Dodder catchment and Casement Aerodrome.

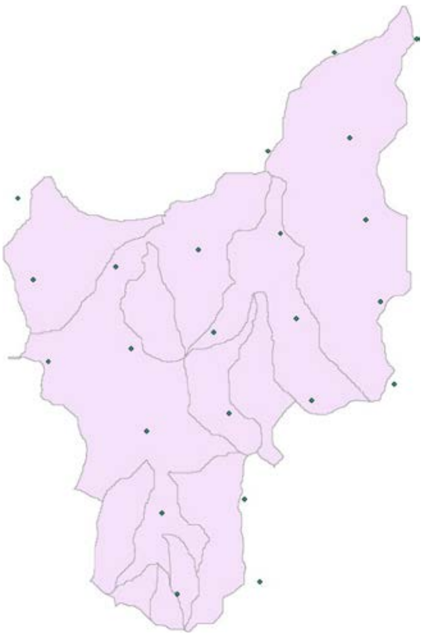

Figure 6.2. Locations of NWP grid points in the Dodder catchment.

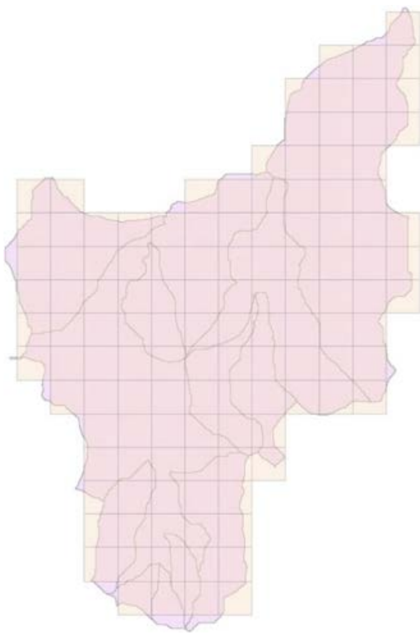

Figure 6.3. Dublin radar precipitation grid overlapping the Dodder catchment.

Figure 6.4 shows the cumulative depths (in mm) for the three different precipitation data sources. The NWP total for the period 2001–2003 is the highest (3223 mm), the rain-gauge total (2900 mm) is next highest and the radar total (2434 mm) is the lowest. The cumulative flow (expressed as mm) is also shown to (i) confirm the rainfall pattern is like that of the flow so that it is representative of areal rainfall for the catchment, (ii) show the smoothing effect of the catchment on the flow series and (iii) illustrate the effective overall runoff coefficient, as a data check. As expected, all the cumulative rainfall series are substantially higher than the cumulative flow (expressed as a depth in mm over the catchment), which is 1801 mm. Radar estimates tend to be lower than rain gauges, for a variety of reasons, and require adjustment, done here by multiplying by a constant adjustment factor of 1.2. This brings the radar

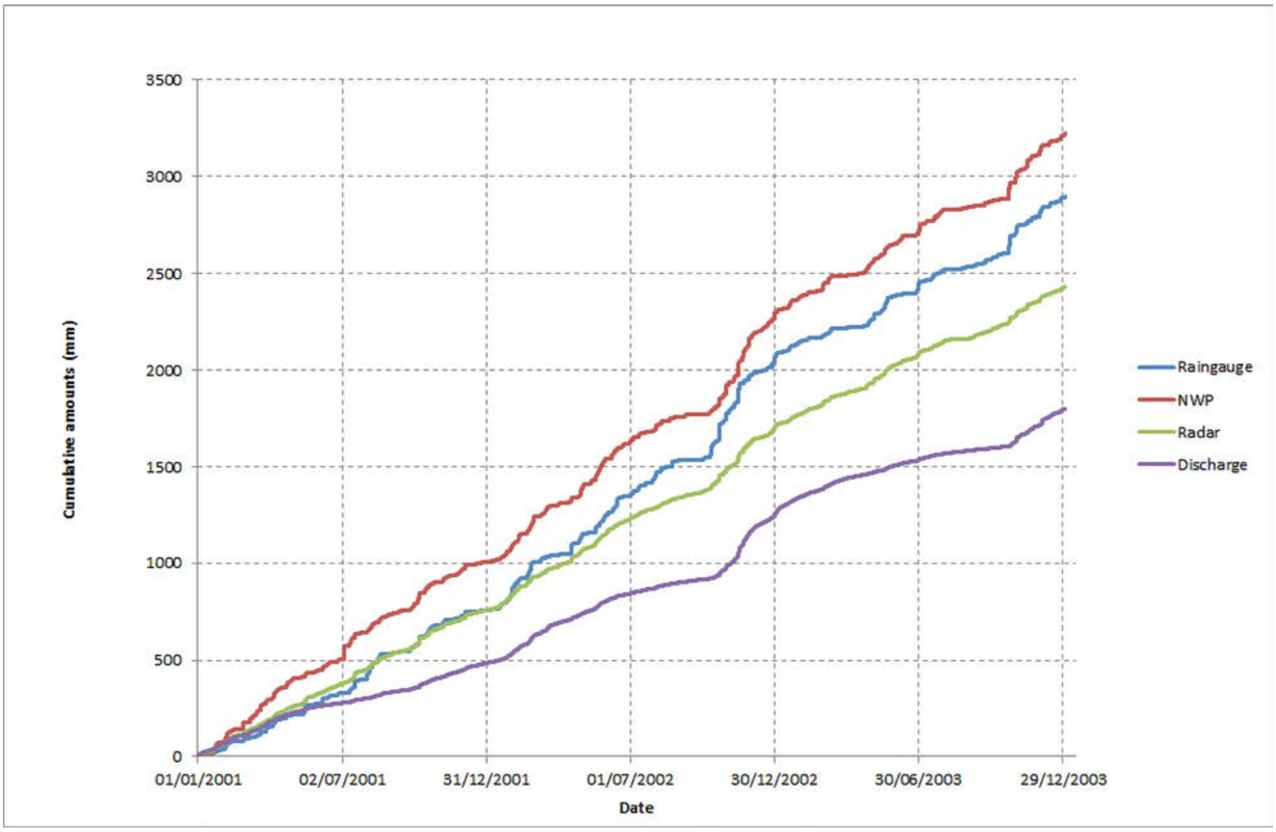

Figure 6.4. Cumulative depths of rain from three data streams and discharge (mm).

precipitation series close to that of the rain gauge, particularly for the later 18 months of the record, but it overestimates for the first 18 months.

6.4.2 Results for the Dodder

The model fitting results for the Dodder, using hourly data, are summarised in Table 6.1 for each of the three different sources of precipitation estimates.

In each case the bias is very small and negative, indicating that, on average, the model has a slight tendency to underestimate flows. The model using precipitation from the NWP reanalysis performs best overall with a Nash–Sutcliffe (NS) coefficient of 0.64, while the corresponding values for rain gauges and radar are 0.59 and 0.58, respectively; none of these is satisfactory. The poor performance of the rain gauges may be due to having to use hourly data from Casement Aerodrome (which is outside the catchment) and scale it for the catchment. The radar is adjusted to have the same total volume of water as the rain-gauge precipitation. Figures 6.5–6.7 illustrate the difficulty in forecasting floods in small, steep catchments. Occasionally a measured high flow is not well modelled and vice versa; in a small number of cases the high flow is forecasted which did not materialise, possibly as a result of differences in spatial distribution of precipitation over the catchment and at Casement Aerodrome.

Table 6.1. Summary of model fitting results (Dodder)

Dodder (hourly time step)	Source of precipitation information		
Index	Rain gauges	NWP	Radar (adjusted)
Bias (mm)	–0.0067	–0.0035	–0.0033
Mean magnitude of residual (mm)	0.023	0.022	0.022
Root mean square residual (mm)	0.054	0.051	0.055
NS criterion	0.59	0.64	0.58

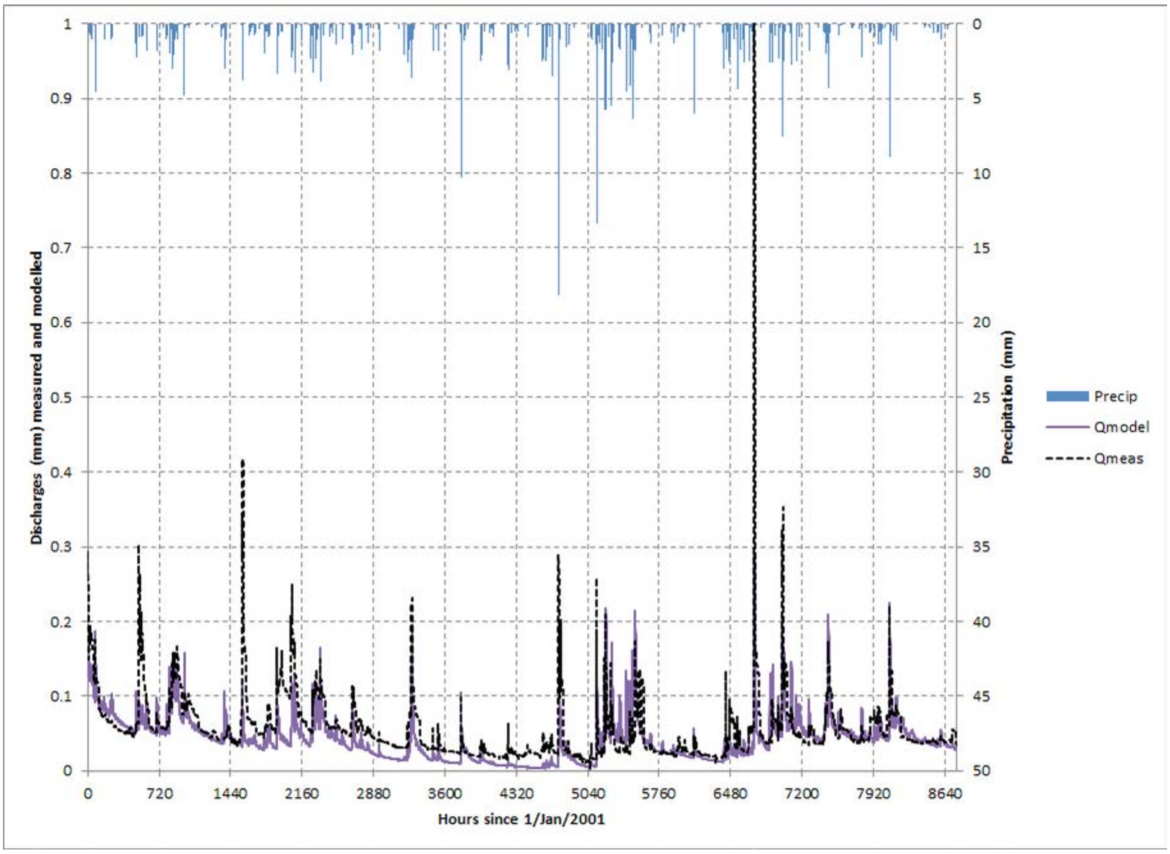

Figure 6.5. Dodder flood forecasts 2001 (hourly) using precipitation from rain gauges.

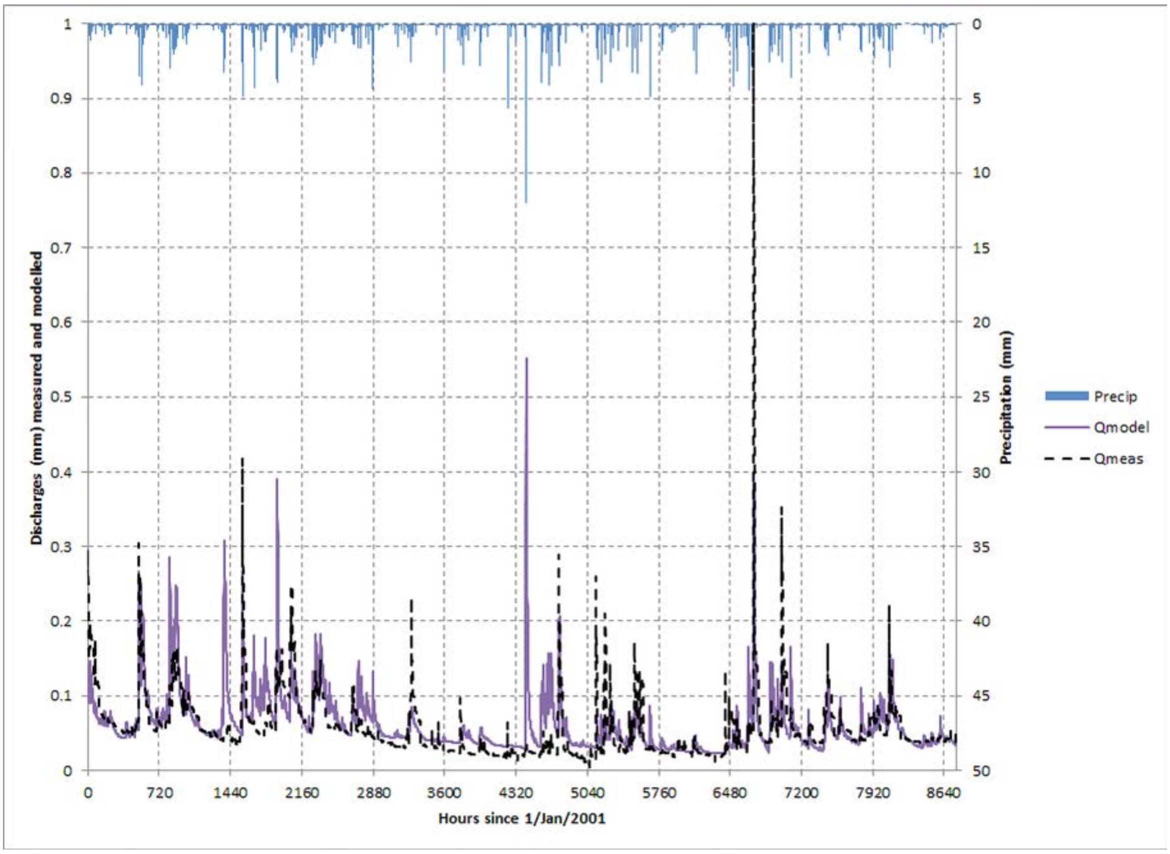

Figure 6.6. Dodder flood forecasts for 2001 (hourly) using precipitation from NWP.

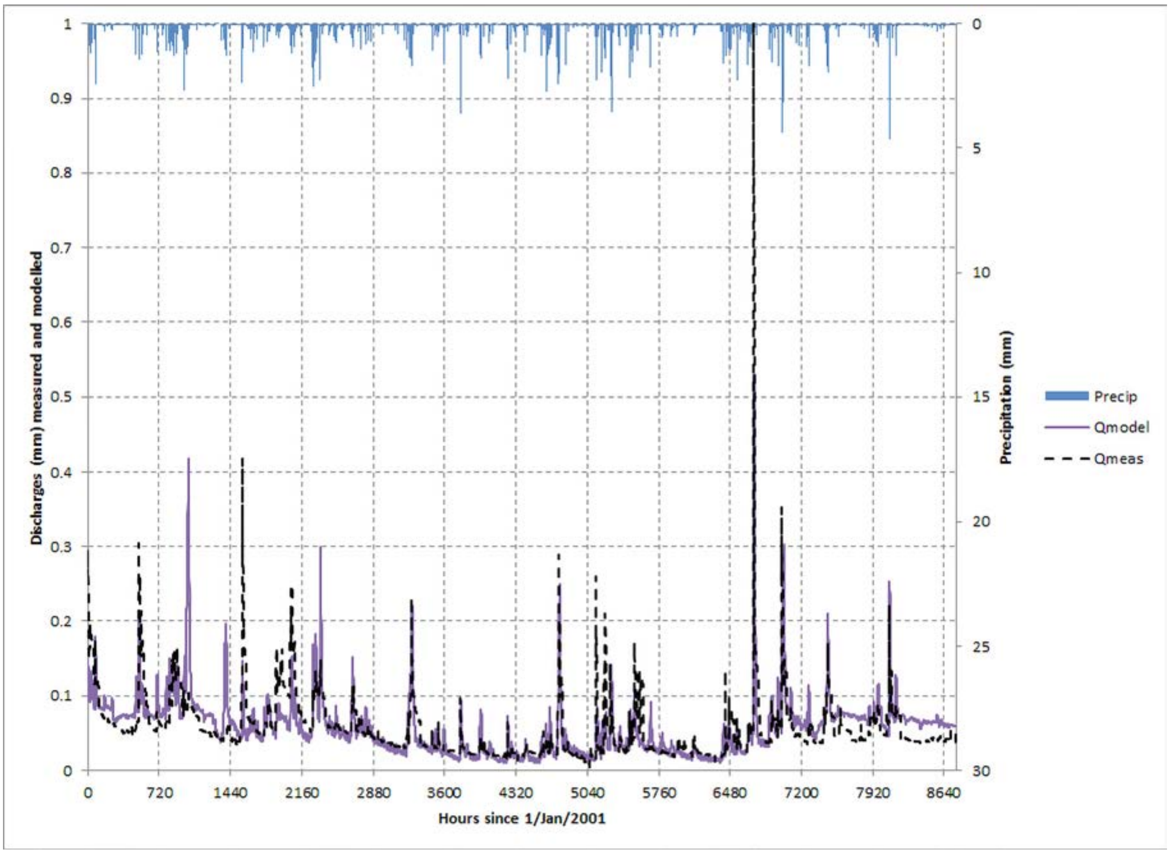

Figure 6.7. Dodder flood forecasts for 2001 (hourly) using precipitation from adjusted radar.

6.5 Suir

The entire Suir catchment, to the coast, has an area of 3610 km². The average rainfall over the catchment is 1030 mm, and the mean annual flow is estimated to be 76.9 m³/s (South Eastern River Basin District; SERBD). It rises north-west of Templemore in the Silvermine Mountains in County Tipperary and drains most of County Tipperary and portions of Counties Waterford, Limerick, Cork, Kilkenny and Laois. It joins the Rivers Nore and Barrow and the combined flow enters the sea at Waterford Harbour. The Suir is 184 km in length and its main channel gradient is estimated to be 2.44 m/km. It contains eight large towns (Waterford, Carrick-on-Suir, Clonmel, Cahir, Cashel, Tipperary, Thurles and Templemore), but it is primarily an agricultural catchment, mainly devoted to pasture, but with some tillage. It has some bogs and forestry. The catchment's soils range from peats and exposed rock in the northern parts of the catchment to gley soils in the river plain. Much of the catchment is underlain by karstified carboniferous limestones.

6.5.1 Data for the Suir catchment

The tidal influence extends upstream of Carrick-on-Suir and long-term discharge records, including for the years 2001–2003, are available for a gauging station at Caher Park. There are 42 rain-gauge stations listed in the Met Éireann database; these seem to give a good coverage of the catchment to Caher Park, but only four of these were open in the period 2001–2003 (Table 6.2), required for this study, as most were closed by then.

The distribution of these stations (the blue dots in Figure 6.8) does not give a satisfactory coverage of the catchment, particularly of its western side, which is likely to receive more rainfall than the eastern side. So, four additional stations that are nearby but outside the catchment were included, but which (with a Thiessen polygon approach) do cover a considerable portion of the western side of the catchment (the red dots in Figure 6.8). The areal rainfall (rain gauges) for the catchment was computed from data for all eight stations.

Table 6.2. Rain-gauge stations open in catchment of Caher Park in 2001–2003

Station no.	Name	Latitude	Longitude	Year in which opened
2012	Cashel (Ballinamona)	52.511	–7.928	1910
6712	Littleton II. (Bord na Mona)	52.611	–7.699	1982
8112	Clonoulty (Clogher)	52.621	–7.934	1994
8712	Thurles (Racecourse)	52.687	–7.831	1999

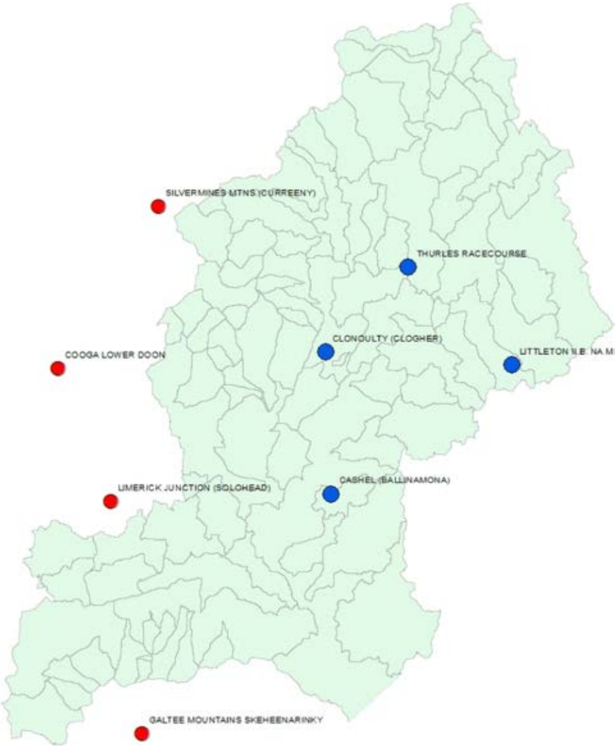

Figure 6.8. Locations of rain gauges used for the Suir catchment (to Caher Park).

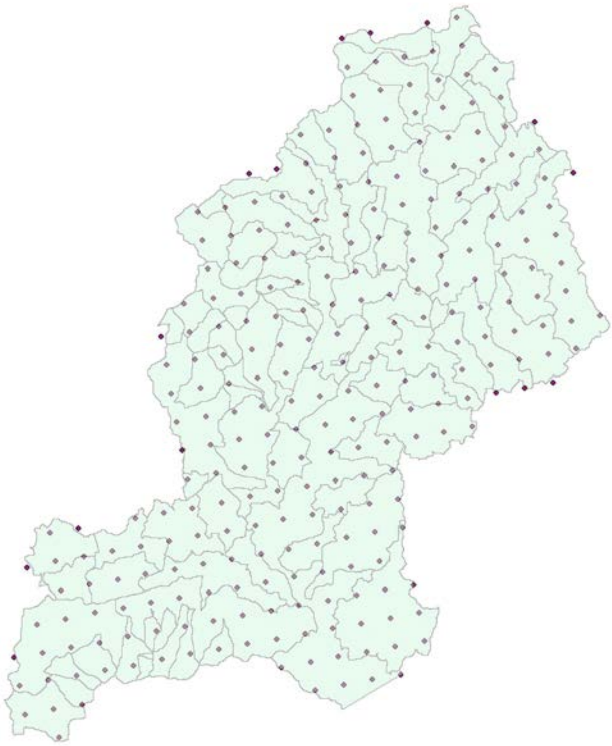

Figure 6.9. Locations of NWP grid points for the Suir catchment (to Caher Park).

The locations of NWP grid points for this catchment are shown in Figure 6.9. The hourly rainfall NWP reanalysis estimates for each of these points were aggregated into daily values and averaged to give areal NWP rainfall for the catchment.

The simulation of the Suir catchment to Caher Park was undertaken for the years 2001–2003 for which precipitation estimates from rain gauges and the NWP reanalysis project were available. For this period the annual average fluxes are as shown in Table 6.3

The Suir catchment is not covered by the Dublin radar, so precipitation is available only from rain-gauge data and from NWP reanalysis. The cumulative depths over the 3 years of record (2001–2003) are shown in Figure 6.10 and these lie close together with a total of 3179 mm for the NWP being slightly higher than the rain-gauge total of 3052 mm. The corresponding depth of flow is 1778 mm.

Table 6.3. Annual average fluxes for the Suir catchment (to Caher Park) for the period 2001–2003

Time series (2001–2003)	Annual average (mm)
Precipitation (rain gauges)	973
Precipitation (NWP)	1011
Discharge	579
Potential evaporation	523
Runoff ratio (rain gauge)	60%
Runoff ratio (NWP)	57%

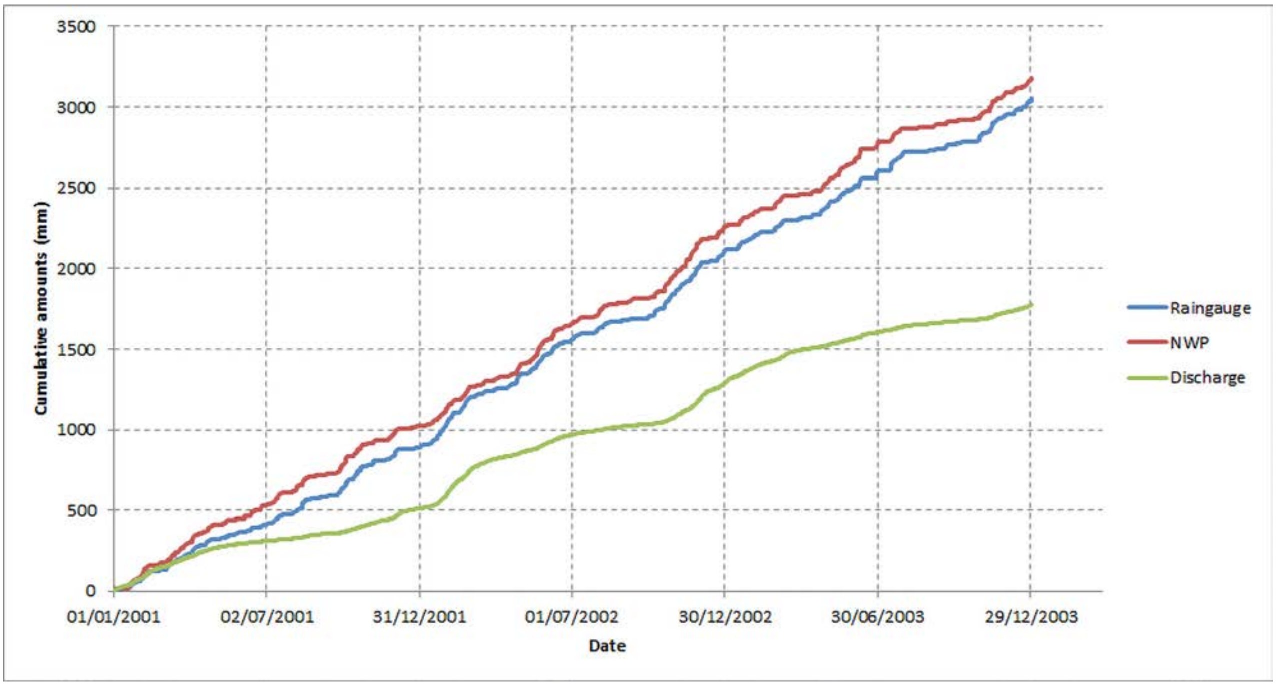

Figure 6.10. Cumulative volumes of precipitation from different data sources (Suir catchment to Caher Park).

6.5.2 Results for the Suir catchment

The results for the Suir catchment for each of the two different sources of precipitation estimates are shown in Table 6.4. The rain-gauge precipitation (using four rain gauges from within the catchment and four external gauges) gave a good fit to the measured flows, with a NS coefficient of 0.83. The modelled flows matched the measured peaks well in magnitude and timing (which are the foci of this study), but the low flows were underestimated by the model.

The ends of long recessions and the limiting low flow values are underestimated. This could be related to the karst nature of much of the catchment, tapping into a more substantial subsurface reservoir of water than is active during higher flows.

The Soil Moisture Attenuation and RouTing (SMART) model calibrates reasonably well, with a NS value of 0.83 and 0.69 when used with the rain gauge and NWP data, respectively. The performance with the rain-gauge data is best, although, in the summer the model underestimates the low flows. However, it has a better match with the high flows, as is required for flood forecasting (Figures 6.11 and 6.12). In contrast, the NWP precipitation estimates more medium-sized summer storms than actually occurred and missed a large event that did occur (Figures 6.11–6.13). This affects the flow forecasts, which have a NS coefficient of 0.69, which is at the lower end of acceptability. The precipitation data set for 2003 seems to fit better than for the other years.

6.6 Boyne

The River Boyne flows eastwards into the Irish Sea at Drogheda. It drains much of County Meath and some

Table 6.4. Summary of model fitting results (Suir catchment)

Suir catchment (daily time step)	Source of precipitation information	
Index	**Rain gauges**	**NWP**
Bias (mm)	–0.083	–0.069
Mean magnitude of residual (mm)	0.37	0.48
Root mean square residual (mm)	0.54	0.73
NS criterion	0.83	0.69

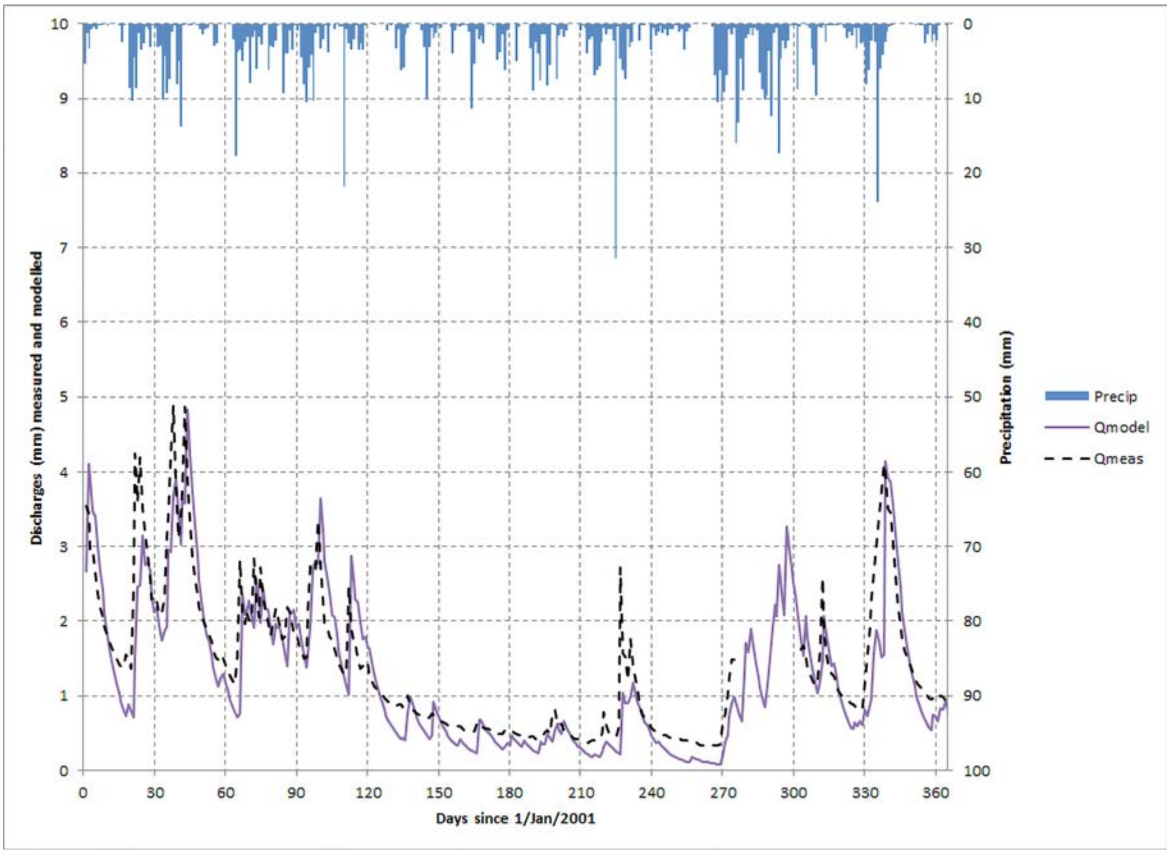

Figure 6.11. Simulation of the Suir catchment for 2001 with precipitation estimates from rain gauges.

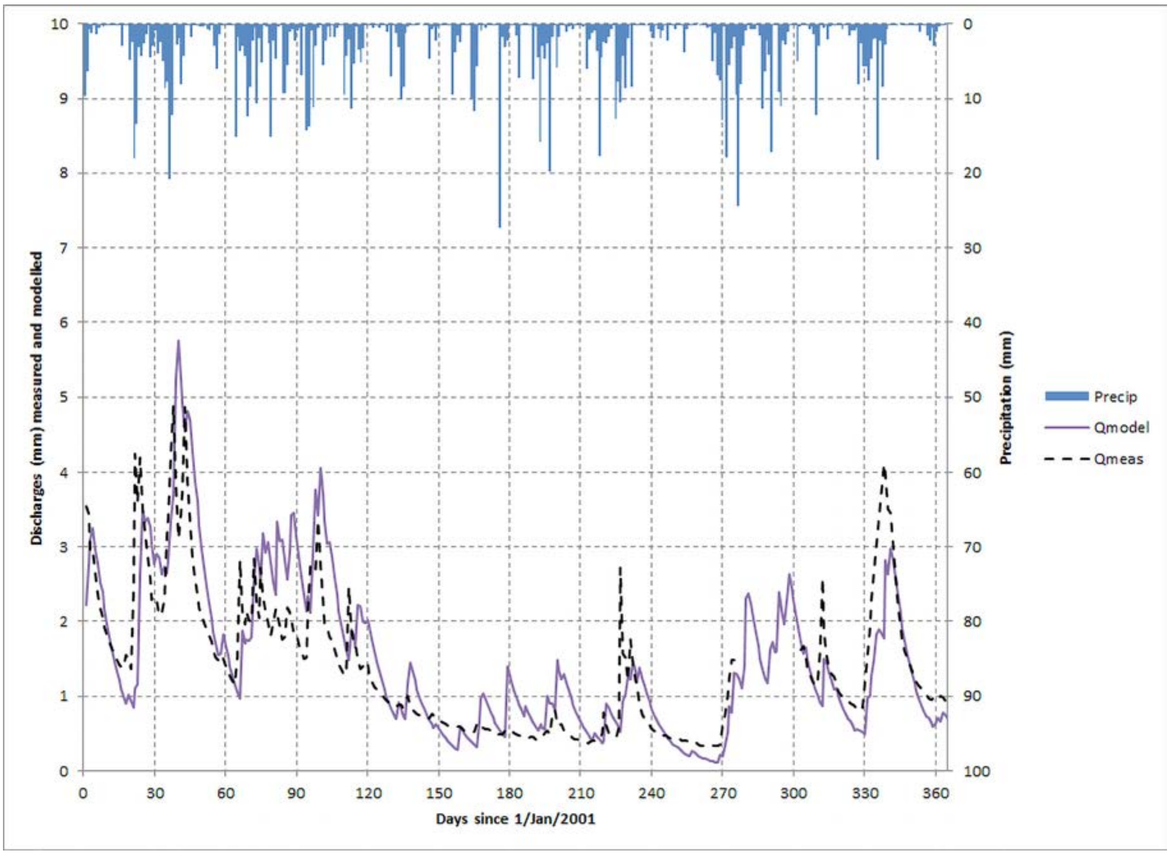

Figure 6.12. Simulation of the Suir catchment for 2001 with precipitation information from NWP.

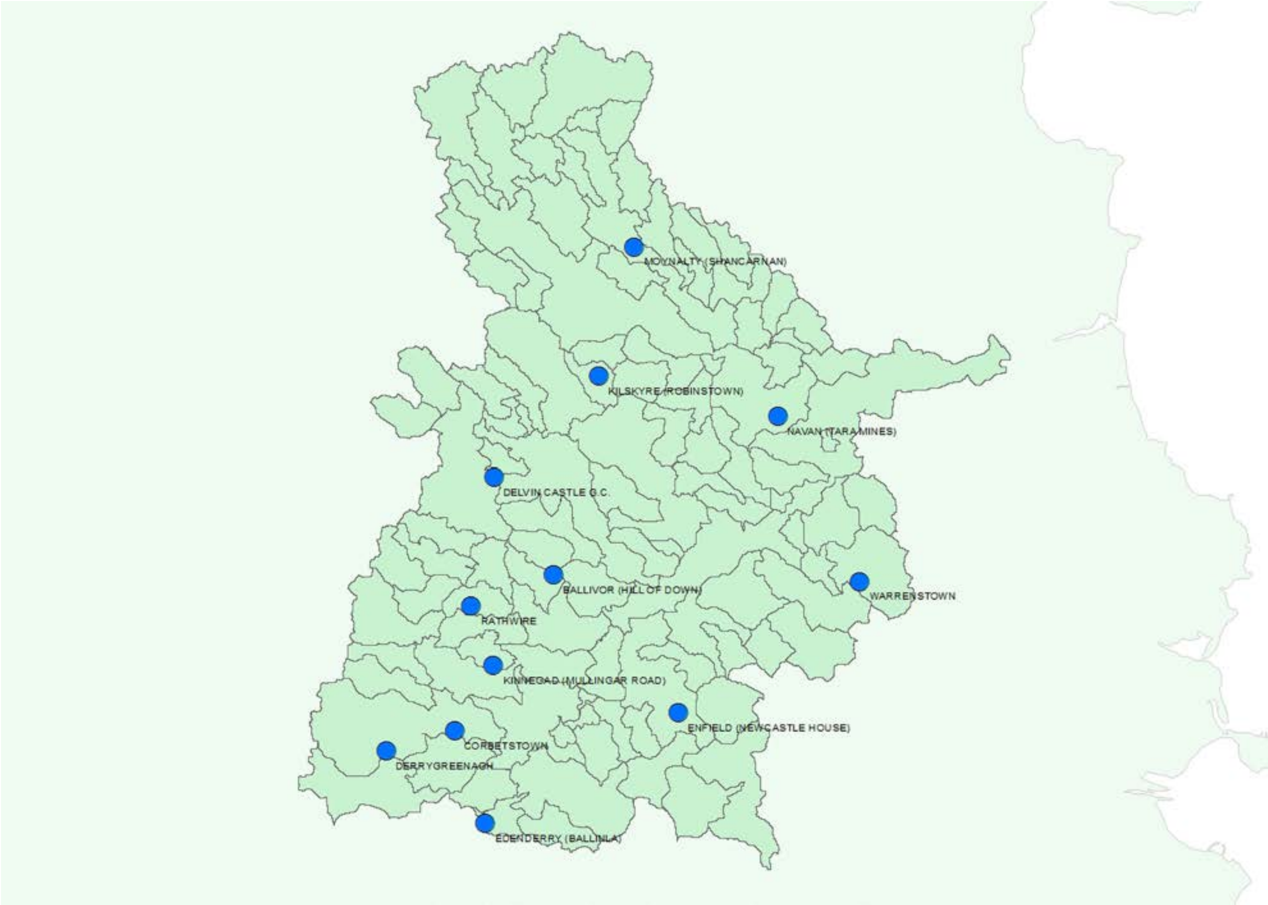

Figure 6.13. Rainfall stations used for the Boyne catchment simulations.

of Counties Cavan, Louth, Westmeath, Offaly and Kildare. The total catchment area is 2693 km^2 and the length of the main channel is 113 km. It is a relatively flat, lowland catchment with an average gradient of 1.24 m/km. The river rises near Edenderry and first flows north-easterly, through Trim and Navan. Its main tributaries are the Kells Blackwater, Yellow River, Kinnegad River, Athboy River, Stonyford River and the Longwood Blackwater. The Boyne river channel was altered between 1970 and 1990 by a substantial arterial drainage scheme and is now maintained (including dredging) by the OPW. The catchment contains some large towns, including Trim, Navan, Kells, Virginia, Bailiboro, Kinnegad, Drogheda and Edenderry. The land is predominantly used for pasture.

6.6.1 Data sources for the Boyne catchment

Precipitation information from rain gauges, radar and NWP are available for the Boyne catchment. The locations of the 12 rainfall stations open in the period 2001–2003 give a good coverage of the catchment (Figure 6.13). The radar grid cells are 1 km^2 in area (shown in Figure 6.14) and the NWP grid points are shown in Figure 6.15. All show a good coverage of this large catchment.

The cumulative depths of rainfall for each of the three sources of information are shown in Figure 6.16. NWP has the highest depth (3042 mm), the combined rain-gauges depth is lower (2565 mm) and the radar far lower again (1728 mm). The latter is not realistic, as it is close to the total flow (expressed as a depth over the catchment for the period 2001–2003 (1386 mm). However, radar is known to underestimate precipitation amounts and, in practice, adjustments are made to the radar estimates based on comparison with rain gauges. This is also done here and the radar data are multiplied by a factor of 1.48. The general patterns of the cumulative curves for each data source are similar and the pattern corresponds with that of the flows. When the radar curve is adjusted, it lies very close to the recorded rain-gauge curve.

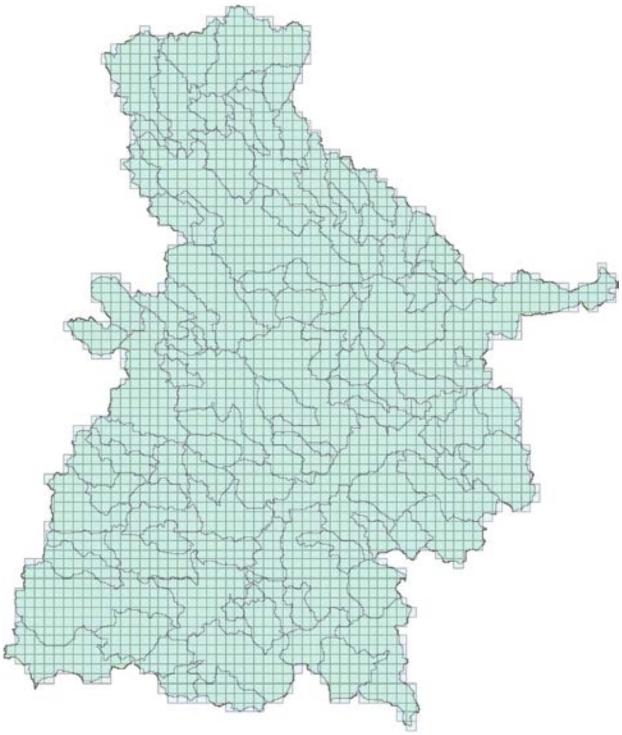

Figure 6.14. Radar grid cells used for the Boyne catchment simulations.

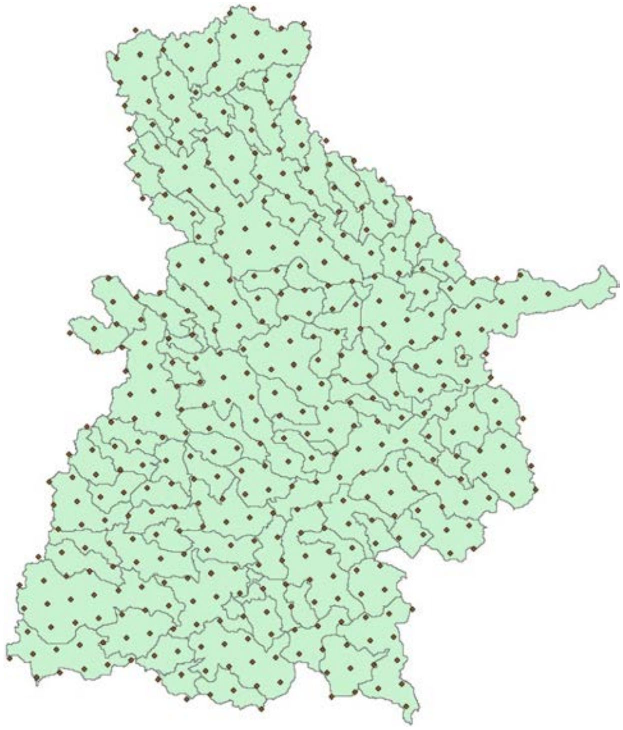

Figure 6.15. Locations of NWP grid points in the Boyne catchment.

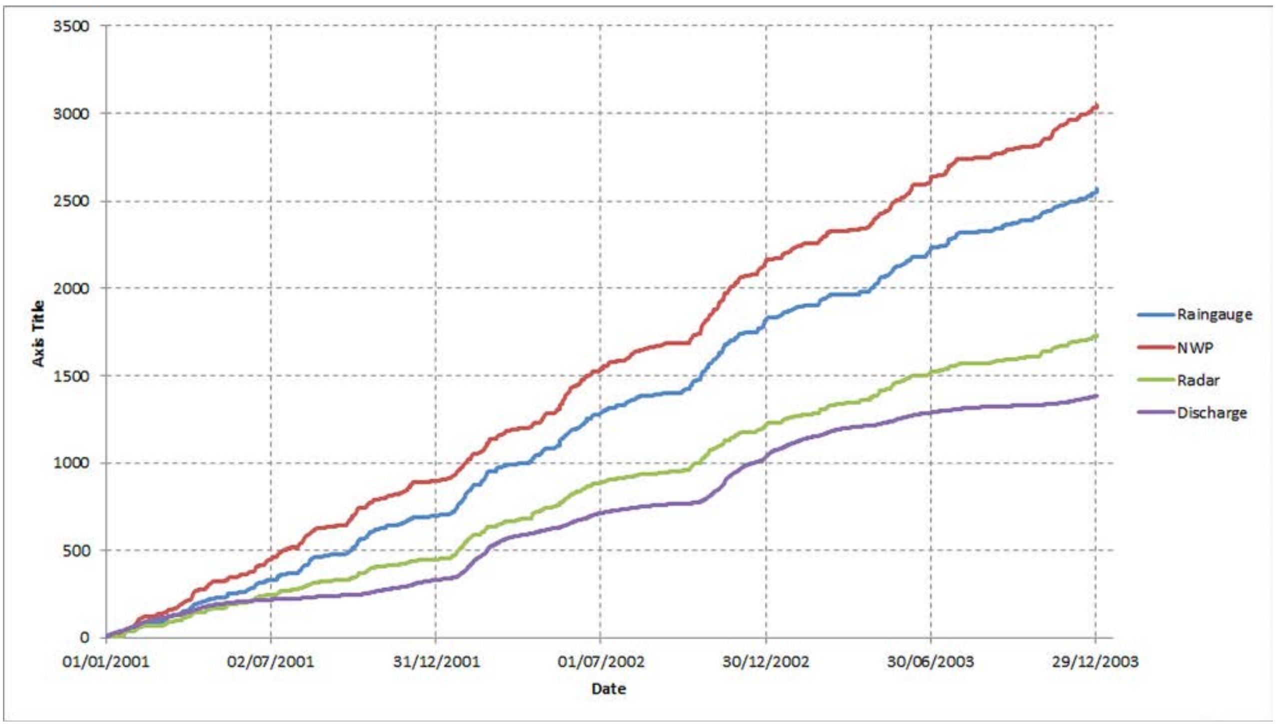

Figure 6.16. Boyne (at Slane Castle) cumulative rain gauge, NWP, radar and discharge depths (mm).

Table 6.5. Annual average fluxes for the Boyne catchment (Slane Castle)

Time series (2001–2003)	Annual average (mm)
Precipitation (rain gauges)	855
Precipitation (RawRadar)	576 (adjusted to 973)
Precipitation (NWP)	1014
Discharge	462
Potential evaporation	506
Runoff ratio (rain gauge)	54%
Runoff ratio (RawRadar)	80%
Runoff ratio (NWP)	46%

The simulation of the Boyne catchment to Slane Castle was undertaken for the years 2001–2003 for which precipitation estimates from rain gauges and the NWP reanalysis project were available. For this period, the annual average fluxes are as shown in Table 6.5.

6.6.2 *Results for the Boyne catchment*

The calibration results for the Boyne catchment are summarised in Table 6.6. Both rain gauges and adjusted radar sources of precipitation gave good simulations, as measured by the NS criterion. However, the rain-gauge data provided the best simulation (NS = 0.89) and the radar (adjusted) was next best (NS = 0.76). The NWP reanalysis, while still giving a reasonable value of the NS criterion (0.7), was not as good as the others and particularly for the higher flows, with many substantially underestimated, it interestingly was the least biased of the methods.

The SMART model calibrates reasonably well, with an NS value of 0.89, 0.70 and 0.76 when used with the rain gauge, NWP and radar (adjusted) data, respectively. The performance with the rain-gauge data is best, although, with a good match to the high flows, as is required for flood forecasting, some of the peaks are overestimated (Figure 6.17). The radar also gives good results, but underestimates the peaks (Figure 6.18). In contrast, the NWT precipitation estimates more medium-sized summer storms than actually occurred (Figure 6.19).

All models were negatively biased, indicating that, on average, they underestimated the measured flows. The reasonably good performance of the Dublin radar is to be expected, as the catchment lies well within the range of the radar's precipitation estimation capability and the intervening terrain is relatively flat, reducing any beam blockage effects. The very good fit of the model using rain-gauge data, compared with precipitation estimates from NWP and radar is apparent from Figures 6.17–6.19, the only blemish being the estimation, in late 2001, of a minor increase in flows that did not materialise.

6.7 Real-time Forecasting Evaluation

The foregoing tests demonstrated the suitability of the SMART model for simulating the rainfall–runoff relationship in the test catchments and evaluated the performance of different sources of precipitation information. The fitting of the model provided a model parameter set for each catchment and for each data source and a set of initial conditions for each model/data source combination. A computer test bed was written to operate the models in real-time forecasting mode to assess their suitability for flood forecasting. The difference between this and the model simulations of the previous section is that in real-time flood forecasting, the system must predict the river discharge one, two, three or more time steps into the future without having any direct measurement of the future flows or the corresponding future rainfalls. In the simulation model, in contrast, the model is optimised to fit all of the historic data set.

Table 6.6. Summary of model fitting results (Boyne catchment)

Boyne catchment (daily time step)	Source of precipitation information		
Index	Rain gauges	NWP	Radar (adjusted)
Bias (mm)	–0.018	–0.001	–0.042
Mean magnitude of residual (mm)	0.20	0.36	0.33
Root mean square residual (mm)	0.41	0.70	0.62
NS criterion	0.89	0.70	0.76

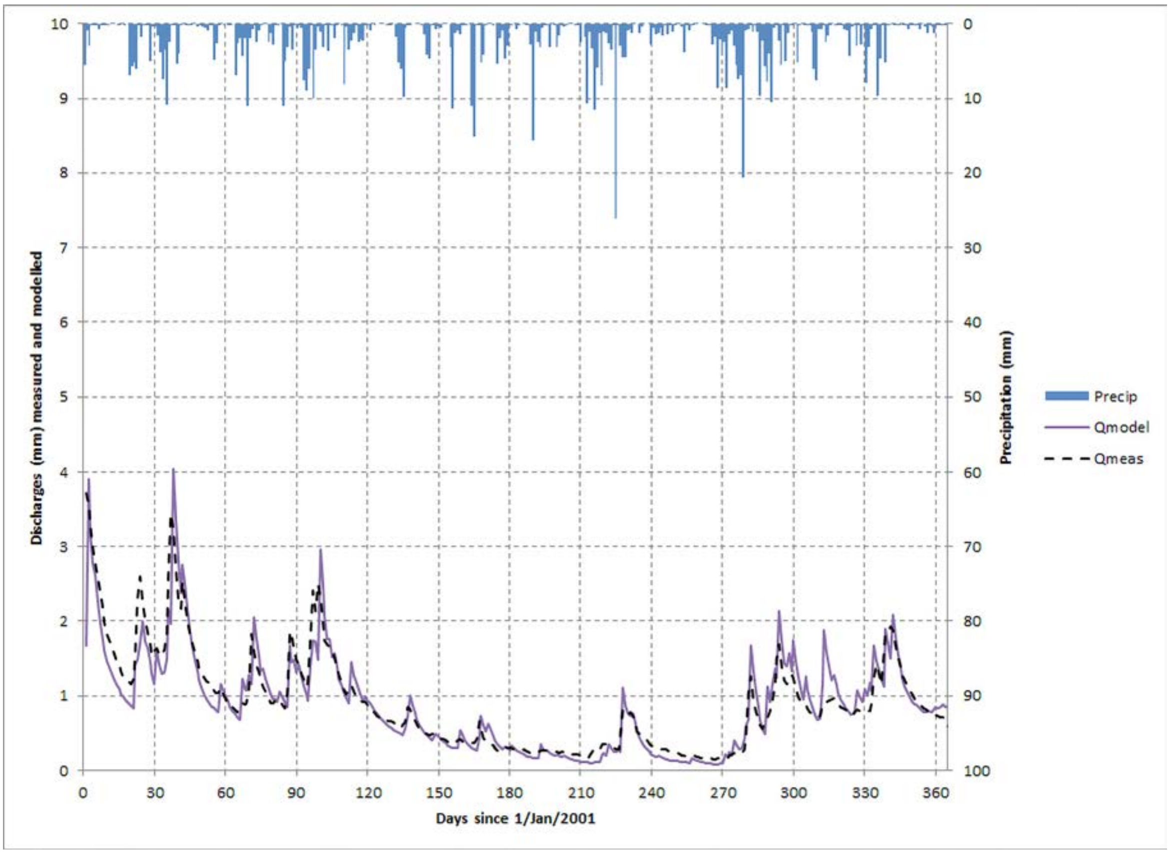

Figure 6.17. Simulation of the Boyne catchment for 2001 with precipitation estimates from rain gauges.

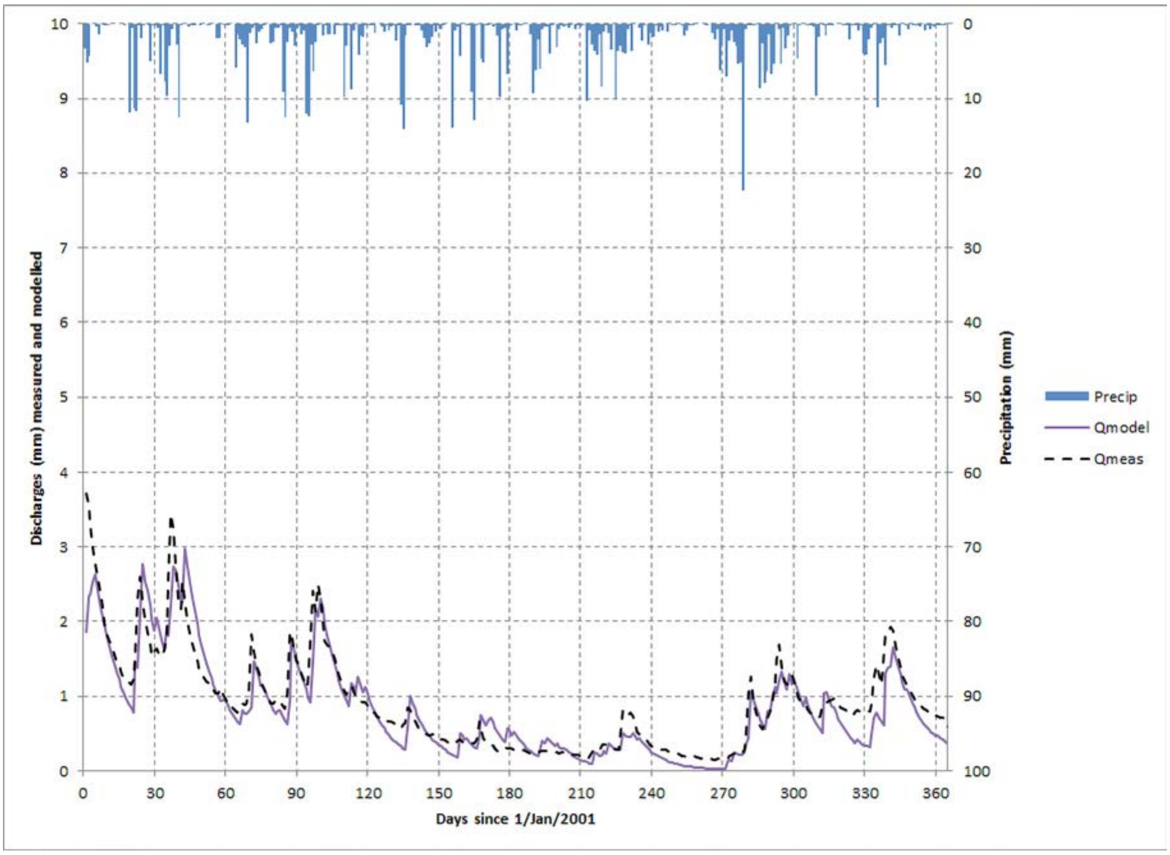

Figure 6.18. Simulation of the Boyne catchment for 2001 with precipitation information from adjusted radar.

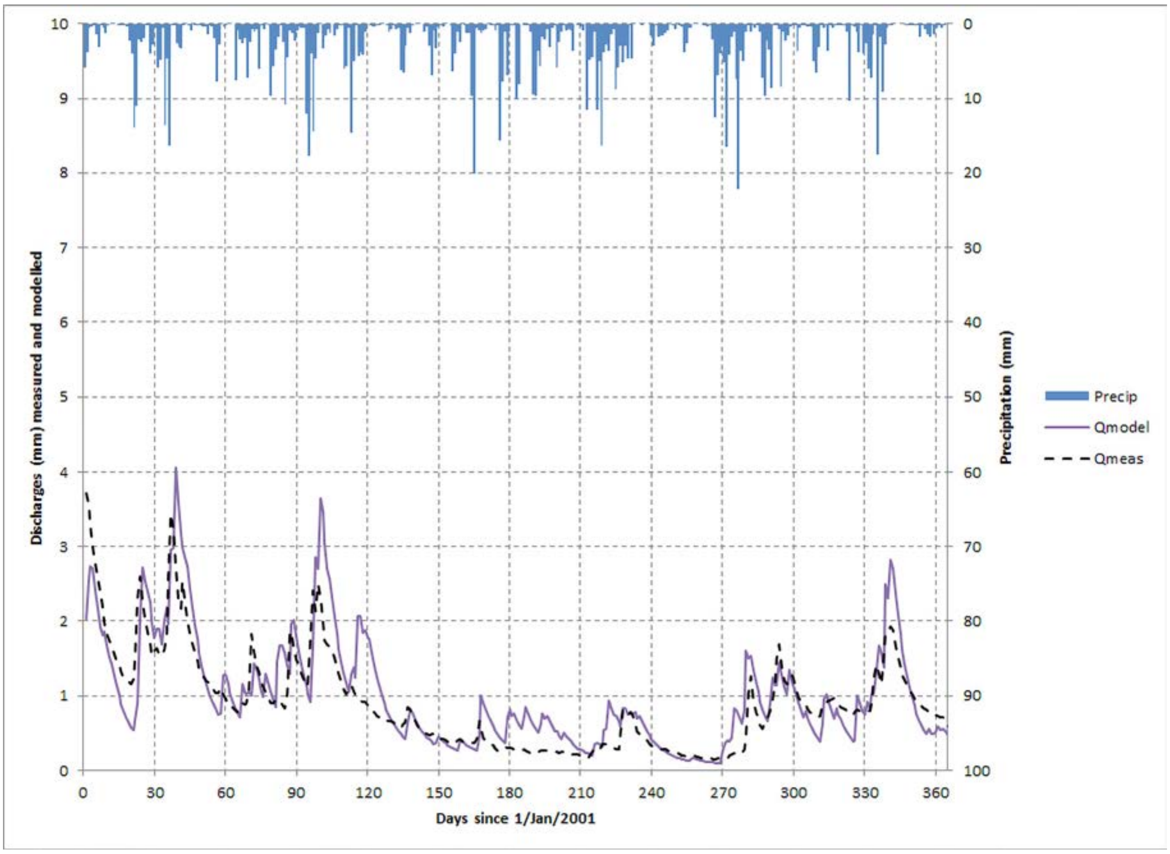

Figure 6.19. Simulation of the Boyne catchment for 2001 with precipitation information from NWP.

In addition to a special numerical test bed to implement these tests, a program was written to forecast rainfall for a specified number of steps into the future for the radar and the rain-gauge data sources. This adopted a two-step statistical approach. Dividing the range of possible rainfall amounts into four ranges (<2, 2–5, 5–10 and >10 mm for the daily rainfall) and (<0.2, 0.2–0.5, 0.5–1 and >1 mm for hourly rainfall), a transition probability matrix was constructed from the measured data sets for each data source. This gave the probability of the rainfall being in any range at the next time step as a function of the range it was in at the current time step. Then, for each combination a mean and variance of the rainfall historically in that category was determined and a random number generator was used to generate an estimated future rainfall amount with the same first two moments as the historical rainfall in each range. This was done separately for the radar and rain-gauge precipitation sources. For the NWP reanalysis, the actual reanalysis estimate was used directly on the basis that this was likely to be an indicator or upper bound on the best estimate a real-time NWP forecasting system could achieve.

The real-time forecasting performance for each of the catchments is shown in Tables 6.7–6.9. Note that the rain-gauge precipitation source does best (considering the NS criterion) up to 3 days ahead, but that for 4-day-ahead forecasting the performance drops off (NS = 0.583) and is worse than for the other data sources. Gauge-adjusted radar is second best and the NWP reanalysis has the lowest values of NS, but its performance does not drop off as rapidly at 4-day-ahead forecasting as the others do.

A similar real-time forecasting test was done for the River Suir, forecasting up to 4 days ahead from precipitation sources. The results are shown in Tables 6.10 and 6.11. Note the NS coefficient is generally lower (i.e. worse) than for the Boyne. Again, the rain-gauge information performs best for the 1-, 2- and 3-day-ahead forecast, but its performance drops off for the 4-day-ahead forecast. While the forecasts using NWP are not as good for 1-, 2- and 3-day-ahead forecasts, there is no drop-off for the 4-day ahead forecast such that its NS value is higher than that for the rain-gauge driven forecasts.

Table 6.7. Real-time flood forecasting for the River Boyne with rain-gauge precipitation source

Criterion	1-day-ahead forecast	2-day-ahead forecast	3-day-ahead forecast	4-day-ahead forecast
Bias	–0.02647	–0.02399	–0.02392	–0.03705
Mean absolute residual	0.29625	0.29525	0.29531	0.38386
Root mean square error	0.64261	0.64051	0.64058	0.82047
NS R^2	0.74427	0.74594	0.74589	0.58313

Table 6.8. Real-time flood forecasting for the River Boyne with NWP precipitation source

Criterion	1-day-ahead forecast	2-day-ahead forecast	3-day-ahead forecast	4-day-ahead forecast
Bias	–0.01113	–0.01025	–0.00857	–0.00918
Mean absolute residual	0.40384	0.40296	0.40327	0.40494
Root mean square error	0.77211	0.77091	0.77128	0.77238
NS R^2	0.63082	0.63197	0.63161	0.63056

Table 6.9. Real-time flood forecasting for the River Boyne with adjusted radar precipitation source

Criterion	1-day-ahead forecast	2-day-ahead forecast	3-day-ahead forecast	4-day-ahead forecast
Bias	–0.01391	–0.01304	–0.01153	–0.0561
Mean absolute residual	0.37998	0.37911	0.37886	0.41684
Root mean square error	0.70049	0.69896	0.69867	0.77201
NS R^2	0.69613	0.69746	0.69771	0.63091

Table 6.10. Real-time flood forecasting for the River Suir with rain-gauge precipitation source

Criterion	1-day-ahead forecast	2-day-ahead forecast	3-day-ahead forecast	4-day-ahead forecast
Bias	–0.03951	–0.03783	–0.03783	–0.03957
Mean absolute residual	0.53034	0.5307	0.53071	0.6139
Root mean square error	0.7736	0.77403	0.77403	0.89774
NS R^2	0.6617	0.66133	0.66132	0.54442

Table 6.11. Real-time flood forecasting for the River Suir with NWP precipitation source

Criterion	1-day-ahead forecast	2-day-ahead forecast	3-day-ahead forecast	4-day-ahead forecast
Bias	–0.01996	–0.01985	–0.01975	–0.0217
Mean absolute residual	0.58646	0.58635	0.58625	0.58636
Root mean square error	0.87713	0.87699	0.87698	0.87768
NS R^2	0.56509	0.56523	0.56524	0.56455

The real-time flood forecasting for the Dodder was carried out at an hourly time step, so the forecasts are for 1, 2, 3 and 4 hours ahead (Tables 6.12–6.14). With the smaller, steeper catchment with a fast response time, the NS values are somewhat lower than for the bigger catchments. However, the rain-gauge data source, despite being outside the catchment at Casement Aerodrome still gives a better performance (NS greater than 0.5) than the other data sources and has a slight drop-off in performance for the 4-day-ahead forecast. The radar data source has a NS criterion around 0.36, which is not good. However, the NWP data source has negative values of NS, indicating that it is not as good as simply forecasting the long-term mean discharge for every step.

6.8 Summary Conclusions

The SMART catchment model was used both in rainfall–runoff simulation and real-time flood forecasting roles for the three test catchments, and with precipitation estimates from rain gauges, radar or NWT individually. Some conclusions are:

1. Despite the poor present-day coverage of some of these catchments with operational rain-gauges, this data source performed better at rainfall–runoff simulation and at real-time flood forecasting (with lead times up to three time steps ahead) than radar or NWP. This strongly supports the value of the Met Éireann rain-gauge network and, considering the reduced number of operational gauges, is an argument for increasing coverage in areas for which flood forecasts are required.
2. Nevertheless, NWP and radar performed well for the bigger catchments (using daily time steps) for which their superior spatial coverage is an advantage. Floods in these larger catchments are more likely to be associated with frontal weather systems, rather than convective and this is a factor in the better performance of radar (Fitzpatrick, 2013).

Table 6.12. Real-time flood forecasting for the River Dodder with rain-gauge precipitation source

Criterion	1-hour-ahead forecast	2-hour-ahead forecast	3-hour-ahead forecast	4-hour-ahead forecast
Bias	–0.00613	–0.00613	–0.00612	–0.0062
Mean absolute residual	0.02308	0.02307	0.02307	0.02361
Root mean square error	0.05591	0.05591	0.05591	0.05771
NS R^2	0.56506	0.56513	0.56517	0.53672

Table 6.13. Real-time flood forecasting for the River Dodder with NWP precipitation source

Criterion	1-hour-ahead forecast	2-hour-ahead forecast	3-hour-ahead forecast	4-hour-ahead forecast
Bias	0.0136	0.01361	0.01361	0.01362
Mean absolute residual	0.06909	0.06909	0.06908	0.06908
Root mean square error	0.15082	0.15082	0.15082	0.15082
NS R^2	–2.16461	–2.1645	–2.16442	–2.16437

Table 6.14. Real-time flood forecasting for the River Dodder with adjusted radar precipitation source

Criterion	1-hour-ahead forecast	2-hour-ahead forecast	3-hour-ahead forecast	4-hour-ahead forecast
Bias	–0.02069	–0.02069	–0.02068	–0.01733
Mean absolute residual	0.02439	0.02439	0.02439	0.02384
Root mean square error	0.0675	0.0675	0.06749	0.06764
NS R^2	0.36611	0.36622	0.36629	0.36345

3. The lumped catchment model approach, as in the SMART model, seems to work well for the larger catchments (areas of thousands of km^2) studied here.

4. Steep, flashy catchments are more challenging for both flood modelling and real-time forecasting, even when the model time steps are smaller.

5. The enforced short data period of 2001–2003 to allow direct comparisons with NWP reanalysis is a limitation of these results. When the full set of MÉRA reanalysis is released, a longer time period should be tested to expand on these conclusions.

6. Met Éireann now has an updated radar system, with higher temporal resolution than the former system, and its performance should be compared with other precipitation data sources for real-time forecasting.

7 Demonstration of Key Components of Flood Forecasting Platforms

The FloodWarnTech project held a demonstration workshop for the steering committee to show in detail how specific flood forecasting systems worked. Two types of system were demonstrated: a widely used complex bespoke system and a simple web browser system. As an example of a complex system, the project team demonstrated a system based on Delft FEWS (based on XML) that is being developed (for the OPW) for the River Suir and also a simple web browser system based on HTML. As this was a live demonstration, there is not a written record; however, some key screenshots follow.

Figure 7.1 shows the structure of the SMART catchment model, used both in the flood modelling and forecasting described in Chapter 6 and in the demonstrations described here. It is an output from the EPA-funded Pathways Project and is an enhancement of the SMAR model originally developed at the Department of Hydrology of the then University College Galway (UCG).

The concept of a simple web browser-based flood forecasting system is shown in Figure 7.2. It consists of a server-based, single technological simulation platform, which exports its result as HTML web pages, which can be easily accessed by any browser on the internet. This was demonstrated at the workshop and Figures 7.3 and 7.4 show a typical simulation for the Griffeen River in County Dublin.

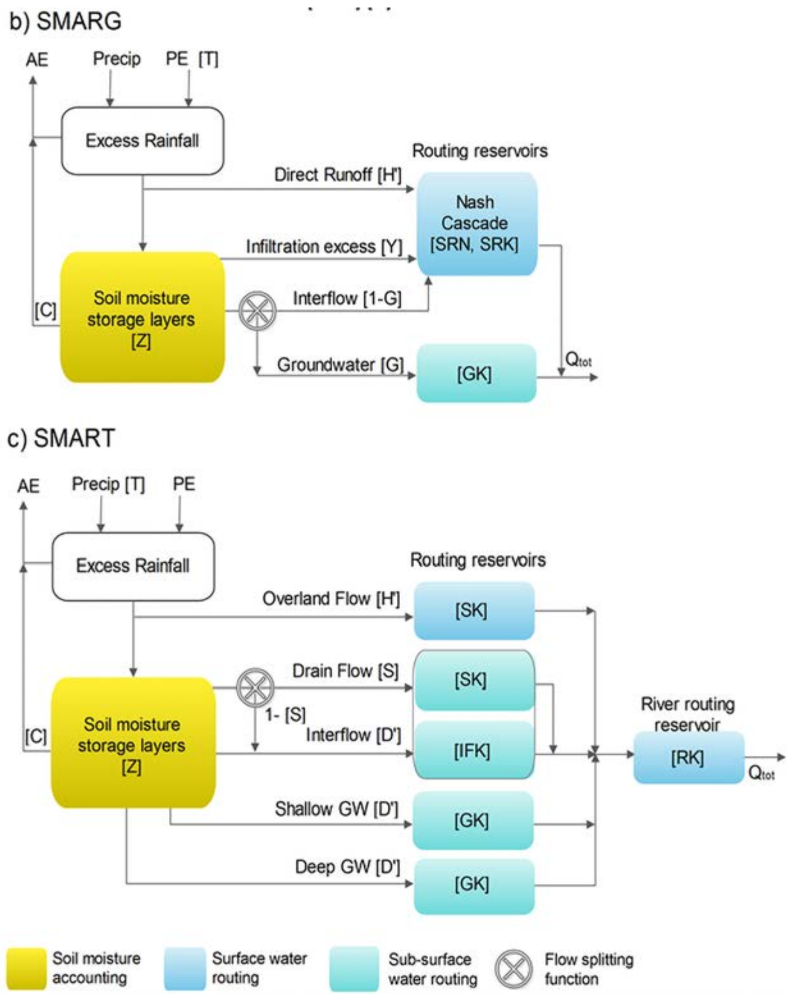

Figure 7.1. Structure of the SMARG and SMART models. Source: Mockler *et al*. (2016).

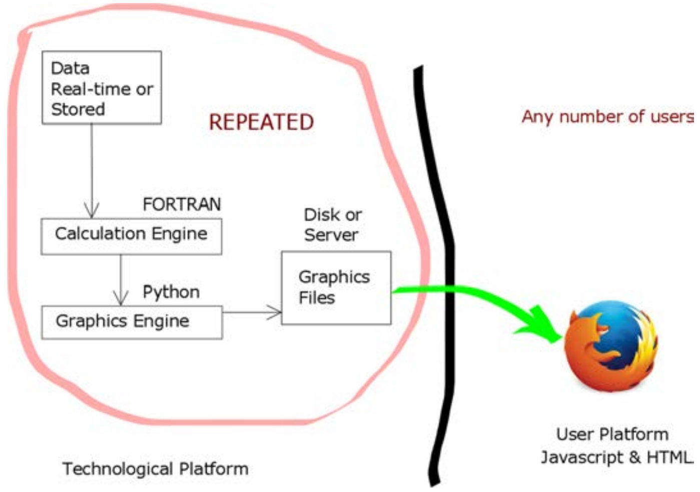

Figure 7.2. Thematic concept of a simple flood forecasting system.

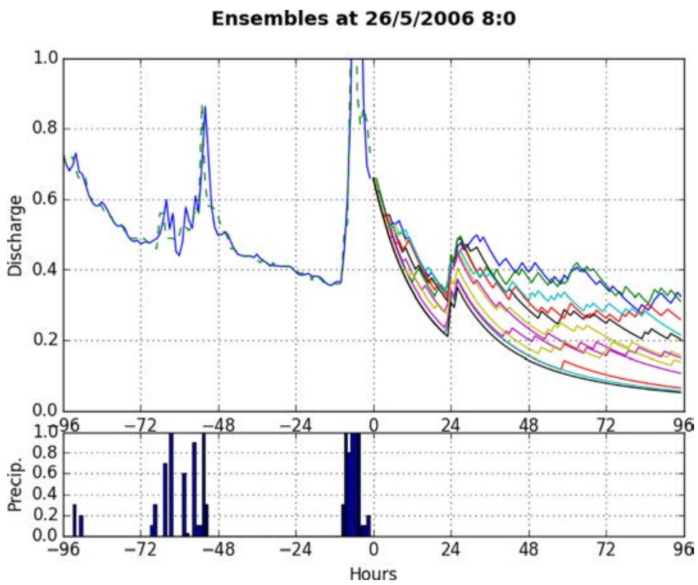

Figure 7.3. Sample output composite graphic generated by the forecasting engine.

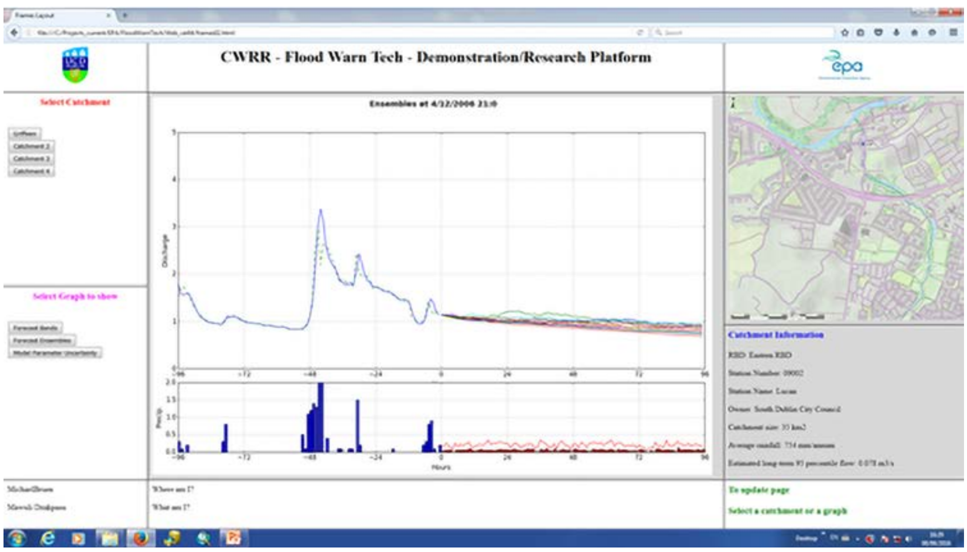

Figure 7.4. Composite graphic as accessed through web browser.

8 Conclusions and Recommendations

8.1 Conclusions

This is the report of a desk study of the technical components required in a flood warning system, with a special focus on Ireland. The key outputs, described in previous chapters and in detail in the main report, are summarised below.

8.1.1 Technical literature review

A review of the published literature on both hydrological and hydraulic models was undertaken and is reported in Chapter 3 together with an assessment of the requirements and capabilities of the major models. Many models are available, although a small number, mainly conceptual catchment models, are in widespread use. An assessment of a number of such models (Mockler *et al.*, 2016) showed that the SMART model performed well in Irish catchments and also allowed for a more robust calibration. Thus, this model was subsequently used in the simulation tests of the precipitation sources and in the demonstration of a flood forecasting platform (Chapters 6 and 7). It is recommended for use whenever a conceptual catchment rainfall–runoff model is required.

A parallel review of flood forecasting platforms was undertaken, both of those available internationally and those used in Ireland. The results are described in Chapter 4. A small number of these are widely used internationally (MIKE OPERATIONS, formerly Floodwatch; Delft-FEWS; and ICMLive, formerly FloodWorks). However, some local operational bespoke systems operate in Ireland and these are described in Chapter 4. For this report, the Delft FEWS system was used as a demonstration because of its ready availability, as it is already in use in Ireland. As most of the international platforms can incorporate a range of models, the choice of platform is related more to operational preferences than to technical limitations.

8.1.2 Practical requirements of warning systems

The project held a workshop, to which a wide range of stakeholders involved in flood warning and response were invited. They were invited to list the practical requirements they considered necessary in warning systems. The workshop recommendation covered a wide range of issues and are described in detail in Chapter 5. The need for a co-ordinated national warning service permeated the discussions, which focused on the detailed requirements. They include the need for:

1. more and better data sources;
2. social and community involvement in flood preparedness and response;
3. more use of media in the dissemination of warnings;
4. modelling improvements, particularly the generation and communication of uncertainty information;
5. more detailed flood response planning at appropriate scales.

8.1.3 Existing systems in Ireland

Information for Irish systems is given in section 4.2; the project workshop also contributed practitioners' experience with forecasting. There was a strong feeling at the project workshop that a flood warning centre with national scope was required.

8.1.4 Assessment of potential of radar and NWP for flood forecasting

Here, flow simulations driven by precipitation estimates from (individual) rain gauges, radar (where available) and NWP were used. The value of terrestrial rain-gauge information was an important conclusion from these comparisons, notwithstanding the availability of radar or NWP. There was a requirement for sub-daily rainfall (e.g. hourly) for small catchments. However, when used in forecasting mode, projections from rain-gauge information are best for flows up to 3 days ahead and both radar and NWP do better for longer lead times, with the drop-off in performance from NWP being less.

8.1.5 Software performance demonstration

The demonstration was held at a specially organised steering committee meeting. The summary report is given in Chapter 7.

8.2 Recommendations

1. The proposed national flood warning services should be implemented as soon as possible.
2. This service should consider the broader aspects of flood warning identified by the workshop participants, especially those listed under section 5.2 above, and including the effective communication of warnings to the public and to decision makers. The generation and use of uncertainty information is recommended.
3. The rain-gauge network has a critical role to play in the performance of flood forecasting systems and should be preserved and enhanced where small catchments contribute to critical floods. This project did not have the resources to consider the use of X-Band radar for these critical areas. This could be a separate study.
4. Both radar and NWP contribute value to flood forecasting, with the potential of NWP to extend useful lead times.
5. Now that the full MÉRA reanalysis data set is available (this project had access to a pre-release 3 year data set courtesy of Mr McGrath), the model simulations and data sources tests done here should be undertaken for the full duration of the data set. This would augment and/or strengthen the conclusions.
6. This project did not examine methods of assimilating upstream stream discharge into forecasting systems (Li *et al.*, 2013, 2015). For a number of the larger rivers in Ireland, this is likely to be of value and should be investigated.

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Abbreviations

ARPA	Italian Regional Agency for the Protection of the Environment
BFEWS	Bandon Flood Early Warning System
BoM	Australian Bureau of Meteorology
CHPS	Community Hydrologic Prediction System
DHI	Danish Hydraulic Institute
EC	European Commission
ECMWF	European Centre for Medium-Range Weather Forecasts
EFAS	European Flood Awareness System
EPA	Environmental Protection Agency
GloFAS	Global Flood Awareness System
HEFS	Hydrological Ensemble Forecast System
IFFS	Initial Flood Forecasting System
JRC	Joint Research Centre
NS	Nash–Sutcliffe
NWP	Numerical weather prediction
OPW	Office of Public Works
PC	Personal Computer
PFFS	Preferred Flood Forecasting System
QPE	Quantitative Precipitation Estimation
QPF	Quantitative Precipitation Forecasting
SMART	Soil Moisture Attenuation and RouTing
STEPS	Short-term Prediction System
URBS	Unified River Basin Simulator
VPR	Vertical Profile of Reflectivity

AN GHNÍOMHAIREACHT UM CHAOMHNÚ COMHSHAOIL
Tá an Ghníomhaireacht um Chaomhnú Comhshaoil (GCC) freagrach as an gcomhshaol a chaomhnú agus a fheabhsú mar shócmhainn luachmhar do mhuintir na hÉireann. Táimid tiomanta do dhaoine agus don chomhshaol a chosaint ó éifeachtaí díobhálacha na radaíochta agus an truaillithe.

Is féidir obair na Gníomhaireachta a roinnt ina trí phríomhréimse:

Rialú: *Déanaimid córais éifeachtacha rialaithe agus comhlíonta comhshaoil a chur i bhfeidhm chun torthaí maithe comhshaoil a sholáthar agus chun díriú orthu siúd nach gcloíonn leis na córais sin.*

Eolas: *Soláthraímid sonraí, faisnéis agus measúnú comhshaoil atá ar ardchaighdeán, spriocdhírithe agus tráthúil chun bonn eolais a chur faoin gcinnteoireacht ar gach leibhéal.*

Tacaíocht: *Bímid ag saothrú i gcomhar le grúpaí eile chun tacú le comhshaol atá glan, táirgiúil agus cosanta go maith, agus le hiompar a chuirfidh le comhshaol inbhuanaithe.*

Ár bhFreagrachtaí

Ceadúnú
Déanaimid na gníomhaíochtaí seo a leanas a rialú ionas nach ndéanann siad dochar do shláinte an phobail ná don chomhshaol:
- saoráidí dramhaíola *(m.sh. láithreáin líonta talún, loisceoirí, stáisiúin aistrithe dramhaíola)*;
- gníomhaíochtaí tionsclaíocha ar scála mór *(m.sh. déantúsaíocht cógaisíochta, déantúsaíocht stroighne, stáisiúin chumhachta)*;
- an diantalmhaíocht *(m.sh. muca, éanlaith)*;
- úsáid shrianta agus scaoileadh rialaithe Orgánach Géinmhodhnaithe *(OGM)*;
- foinsí radaíochta ianúcháin *(m.sh. trealamh x-gha agus radaiteiripe, foinsí tionsclaíocha)*;
- áiseanna móra stórála peitril;
- scardadh dramhuisce;
- gníomhaíochtaí dumpála ar farraige.

Forfheidhmiú Náisiúnta i leith Cúrsaí Comhshaoil
- Clár náisiúnta iniúchtaí agus cigireachtaí a dhéanamh gach bliain ar shaoráidí a bhfuil ceadúnas ón nGníomhaireacht acu.
- Maoirseacht a dhéanamh ar fhreagrachtaí cosanta comhshaoil na n-údarás áitiúil.
- Caighdeán an uisce óil, arna sholáthar ag soláthraithe uisce phoiblí, a mhaoirsiú.
- Obair le húdaráis áitiúla agus le gníomhaireachtaí eile chun dul i ngleic le coireanna comhshaoil trí chomhordú a dhéanamh ar líonra forfheidhmiúcháin náisiúnta, trí dhíriú ar chiontóirí, agus trí mhaoirsiú a dhéanamh ar leasúchán.
- Cur i bhfeidhm rialachán ar nós na Rialachán um Dhramhthrealamh Leictreach agus Leictreonach (DTLL), um Shrian ar Shubstaintí Guaiseacha agus na Rialachán um rialú ar shubstaintí a ídíonn an ciseal ózóin.
- An dlí a chur orthu siúd a bhriseann dlí an chomhshaoil agus a dhéanann dochar don chomhshaol.

Bainistíocht Uisce
- Monatóireacht agus tuairisciú a dhéanamh ar cháilíocht aibhneacha, lochanna, uiscí idirchriosacha agus cósta na hÉireann, agus screamhuiscí; leibhéil uisce agus sruthanna aibhneacha a thomhas.
- Comhordú náisiúnta agus maoirsiú a dhéanamh ar an gCreat-Treoir Uisce.
- Monatóireacht agus tuairisciú a dhéanamh ar Cháilíocht an Uisce Snámha.

Monatóireacht, Anailís agus Tuairisciú ar an gComhshaol
- Monatóireacht a dhéanamh ar cháilíocht an aeir agus Treoir an AE maidir le hAer Glan don Eoraip (CAFÉ) a chur chun feidhme.
- Tuairisciú neamhspleách le cabhrú le cinnteoireacht an rialtais náisiúnta agus na n-údarás áitiúil *(m.sh. tuairisciú tréimhsiúil ar staid Chomhshaol na hÉireann agus Tuarascálacha ar Tháscairí)*.

Rialú Astaíochtaí na nGás Ceaptha Teasa in Éirinn
- Fardail agus réamh-mheastacháin na hÉireann maidir le gáis cheaptha teasa a ullmhú.
- An Treoir maidir le Trádáil Astaíochtaí a chur chun feidhme i gcomhair breis agus 100 de na táirgeoirí dé-ocsaíde carbóin is mó in Éirinn.

Taighde agus Forbairt Comhshaoil
- Taighde comhshaoil a chistiú chun brúnna a shainaithint, bonn eolais a chur faoi bheartais, agus réitigh a sholáthar i réimsí na haeráide, an uisce agus na hinbhuanaitheachta.

Measúnacht Straitéiseach Timpeallachta
- Measúnacht a dhéanamh ar thionchar pleananna agus clár beartaithe ar an gcomhshaol in Éirinn *(m.sh. mórphleananna forbartha)*.

Cosaint Raideolaíoch
- Monatóireacht a dhéanamh ar leibhéil radaíochta, measúnacht a dhéanamh ar nochtadh mhuintir na hÉireann don radaíocht ianúcháin.
- Cabhrú le pleananna náisiúnta a fhorbairt le haghaidh éigeandálaí ag eascairt as taismí núicléacha.
- Monatóireacht a dhéanamh ar fhorbairtí thar lear a bhaineann le saoráidí núicléacha agus leis an tsábháilteacht raideolaíochta.
- Sainseirbhísí cosanta ar an radaíocht a sholáthar, nó maoirsiú a dhéanamh ar sholáthar na seirbhísí sin.

Treoir, Faisnéis Inrochtana agus Oideachas
- Comhairle agus treoir a chur ar fáil d'earnáil na tionsclaíochta agus don phobal maidir le hábhair a bhaineann le caomhnú an chomhshaoil agus leis an gcosaint raideolaíoch.
- Faisnéis thráthúil ar an gcomhshaol ar a bhfuil fáil éasca a chur ar fáil chun rannpháirtíocht an phobail a spreagadh sa chinnteoireacht i ndáil leis an gcomhshaol *(m.sh. Timpeall an Tí, léarscáileanna radóin)*.
- Comhairle a chur ar fáil don Rialtas maidir le hábhair a bhaineann leis an tsábháilteacht raideolaíoch agus le cúrsaí práinnfhreagartha.
- Plean Náisiúnta Bainistíochta Dramhaíola Guaisí a fhorbairt chun dramhaíl ghuaiseach a chosc agus a bhainistiú.

Múscailt Feasachta agus Athrú Iompraíochta
- Feasacht chomhshaoil níos fearr a ghiniúint agus dul i bhfeidhm ar athrú iompraíochta dearfach trí thacú le gnóthais, le pobail agus le teaghlaigh a bheith níos éifeachtúla ar acmhainní.
- Tástáil le haghaidh radóin a chur chun cinn i dtithe agus in ionaid oibre, agus gníomhartha leasúcháin a spreagadh nuair is gá.

Bainistíocht agus struchtúr na Gníomhaireachta um Chaomhnú Comhshaoil
Tá an ghníomhaíocht á bainistiú ag Bord lánaimseartha, ar a bhfuil Ard-Stiúrthóir agus cúigear Stiúrthóirí. Déantar an obair ar fud cúig cinn d'Oifigí:
- An Oifig um Inmharthanacht Comhshaoil
- An Oifig Forfheidhmithe i leith cúrsaí Comhshaoil
- An Oifig um Fianaise is Measúnú
- Oifig um Chosaint Radaíochta agus Monatóireachta Comhshaoil
- An Oifig Cumarsáide agus Seirbhísí Corparáideacha

Tá Coiste Comhairleach ag an nGníomhaireacht le cabhrú léi. Tá dáréag comhaltaí air agus tagann siad le chéile go rialta le plé a dhéanamh ar ábhair imní agus le comhairle a chur ar an mBord.

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FloodWarnTech Synthesis Report: Flood Warning Technologies for Ireland

Authors: Michael Bruen and Mawuli Dzakpasu

Identifying Pressures

This report is a response to the growing public and official pressure for Ireland to develop a world class flood forecasting capability to enhance the security of its citizens. It addresses some of the technical and modelling issues that must be resolved to respond to the pressure for an effective flood forecasting service. River flooding is a serious and contentious issue in Ireland, with most of its residential, industrial and transport infrastructure situated near watercourses with low gradients that frequently flood. Although some major structural flood protection schemes have been constructed by the Office of Public Works (OPW) and more are planned, cost–benefit requirements and public/stakeholder considerations are increasing the public pressure for bespoke non-structural solutions and these require operational flood forecasting and warning systems.

Informing Policy

A strong case for a national flood forecasting centre has already been made and the Irish Government has set up a flood warning facility, operated by Met Éireann, in collaboration with the OPW. This project has reviewed international practice to inform appropriate technological decisions in the development of such a flood forecasting centre. In the context of the implementation of the EU Floods Directive, which has sparked the development of flood management schemes for the major flood risk areas of Ireland, information on the balance between physical protection and flood warning measures is necessary for cost-effective solutions.

Developing Solutions

In response to the increasing public pressure for non-structural solutions to flood protection, demountable barriers and other temporary arrangements that are mobilised when a flood is forecast have been increasingly incorporated into flood protection schemes in Ireland. These allow normal access to rivers and flood-prone areas when no flood is forecast, but can be mobilised when a flood is expected. For these to be effective, an appropriate and timely warning of a flood event is required to enable flood managers to make decisions with regard to the activation of the demountable defences, blocking of roads and access to high-risk areas, etc. Such warnings must have a sufficient lead time to allow the defences to be erected and must also be reliable so that flood managers can have confidence in the decisions that ensue. This project has examined both the forecast lead time and the reliability of the best available technologies being used [hydrological, hydraulic models, telemetry from gauges, radar and numerical weather forecasting (for areas with rapid hydrological response times)]. This project was carried out in two stages. First, the issues were explored in a stakeholder workshop, which determined the immediate needs and future requirements of a wide range of stakeholders. This was followed by an examination of the capabilities of existing technologies used internationally in Irish conditions to enable them to be considered for implementation in operational warning systems. The project demonstrated selected examples of these technologies in a workshop, which showed the range of possibilities, from the simple to the sophisticated. Thus, the project provides practical, implementation-oriented information on existing and required technical capabilities, tailored, with examples, to the scales and situations typical of Irish rivers.

The project implemented a hydrological forecast model for three test catchments of different sizes and with different degrees of data availability. In each, it compared the ability of the model to simulate flows with different sources of precipitation data. This project confirmed that effective flood warning solutions for large rivers are best based on good telemetry of real-time measurements of precipitation, together with the appropriate hydrological and hydraulic models. Although the use of upstream water levels was not assessed in this project, these are also expected to contribute to better forecasts in larger catchments. However, for many of the smaller Irish rivers with shorter lead times, the project shows that a good warning solution must not wait until the precipitation has occurred; it must predict the precipitation in advance and the performance of the warning system depends critically on the ability to make these predictions. Although the project has demonstrated the importance of the terrestrial rain-gauge network, it has also explored the performance and the added value of radar and numerical atmospheric model information for flood warning.

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Phone: 01 268 0100
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