Western CFRAM
Unit of management 29 – Galway Bay South East Hydrology Report

Final report

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Contract

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Purpose

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Executive Summary

This report describes the hydrological analysis carried out as part of the Catchment-Based Flood Risk Assessment and Management Study (CFRAM) for the Western River Basin. It covers unit of management (UoM) 29, Galway Bay South East.

The brief calls for a comprehensive and detailed hydrological analysis that places particular emphasis on flood flow estimation for the main flood risk areas (termed AFAs, Areas for Further Assessment) and the watercourses that flow through these areas (termed HPWs, High Priority Watercourses). In UoM 29, the AFAs are Oranmore, Athenry, Gort, Loughrea and Kinvarra. Kinvarra is subject to coastal flood risk, while the other four AFAs are vulnerable to fluvial risk, and Gort is also at risk of groundwater flooding.

The principal objective of the hydrological study is to derive best estimates of design fluvial flood parameters including peak flows, hydrographs and flood volumes, for all hydrological estimation points. The study also includes derivation of design coastal flood parameters for AFAs subject to significant coastal flood risk. The word "design" here refers to a quantity that is expected to be exceeded with a specified probability or frequency, as opposed to a measured river flow or sea level for any particular date and time. Design flood parameters are estimated by statistical analysis or modelling.

The report includes a review of the hydrological data available in the study area. There are several gauging stations that measure river level, some of which have rating equations that enables conversion of level into flow. None of the AFAs has a flow gauging station on site, although there are level gauges at Oranmore and Lough Rea. Loughrea, Athenry and Gort have flow data available either further downstream or upstream on the same watercourse, although there are limitations associated with each gauge.

A variety of methods are available for estimation of design floods. The approach taken for most parts of the Western CFRAM study area is to base the analysis closely on the recorded flow data, in accordance with the methods developed during the Flood Studies Update research. The implementation of the FSU research project has not yet been completed and so it has been necessary to develop software to apply some of the methods.

Peak flows have been estimated from statistical analysis of annual maximum flows. At locations without flow data, design flows have been estimated indirectly from physical properties of the catchment, combined with transfer of data from representative gauged catchments both locally and further afield throughout Ireland. For the most extreme design floods (annual probabilities below 1%), the statistical analysis has been supplemented with an extended flood growth curve from the Flood Studies Report rainfall-runoff method.

The design flows have been derived by direct analysis of flood data so they will naturally be consistent with that data. However design flows have been checked to identify any results that fall outside expected ranges; these included confirmation that growth factors are within expected ranges, that AEPs for observed events implied in the flood frequency curves are appropriate and that there was spatial consistency between design flows.

Several approaches have been trialled for the estimation of design flood hydrographs, and the results assessed using techniques such as analysis of percentage runoff and flood volumes. The recommended approach for most watercourses is to derive the shape of design hydrographs using the rainfall-runoff method from the Flood Studies Report.

A different method of flood estimation has been recommended for the AFA at Loughrea, using the Flood Studies Report rainfall-runoff method in conjunction with flood routing to account for the attenuation that occurs as the flood hydrograph passes through Lough Rea.

Methods used to estimate design flood hydrographs at each AFA

AFA	Watercourse	QMED method	Growth curve method	Distribution	Hydrograph shape
Oranmore	Carrowmoneash, Ballynageeha, Rocklands, Moneyduff	Catchment Descriptors (altered from Data Transfer – Pivotal 29004)	Pooled	General Logistic	FSR rainfall-runoff
Athenry	Graigabbey River	Catchment Descriptors (altered from Data Transfer – Pivotal 29004)	Pooled	Generalised Extreme Value	FSR rainfall-runoff
Loughrea	St Clearan's River and Lough Rea outlet channel	n/a: Design flood hydrographs downstream of Lough Rea outlet to be estimated using the FSR rainfall-runoff method, routed through the lough.			
	Tonaroasty (tributary that does not discharge from lough)	Data Transfer – Pivotal 29007	Pooled	General Logistic	FSR rainfall-runoff
Gort	River Gort, Ballyhugh	To be confirmed in hydraulics report	Pooled, to be confirmed	General Logistic, to be confirmed	FSR rainfall-runoff, to be confirmed

The design flood hydrographs will form inflows to the hydraulic models that are being used to predict flood levels, depths and extents. It has been necessary to reconcile flows within the model with hydrological estimates of flow to ensure consistency through the river systems, and consider the main assumptions and sources of uncertainty in the design flows, and how these are translated into the model.

As well as design flows for the present-day situation, the study has produced a set of flows for two future scenarios, which have considered climate change impacts on both river flows and sea levels and the impact of increased urbanisation. It is considered that land use change, in the form of changes to forestry practice, will have little impact on flood risk in the UoM, so this has not been accounted for.

To provide a downstream boundary condition for hydraulic models of rivers that enter the sea, design tidal graphs have been created by combining information on extreme sea levels with design surge shapes and design astronomical tide curves.

Detailed records of the calculations are provided in the appendices, along with a table of the design peak flows. The report is accompanied by digital deliverables which provide the design flows for all locations, along with further information on the methods used at each location.

The Hydrology Report for UoM 29 should be read in conjunction with the Hydraulic Modelling Report for UoM 29, and the specific modelling reports for each AFA, which detail the application of the hydrology to the specific river reaches.

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Abbreviations

AEP .... Annual exceedance probability
AFA .... Area for further assessment
AMAX .... Annual maximum
CFRAM .... Catchment flood risk assessment and management
DAD .... Defence asset database
DAS .... Defence asset survey
DEM .... Digital elevation model (Includes surfaces of structures, vegetation, etc)
DTM .... Digital terrain model ('bare earth' model; does not include surfaces of structures, vegetation, etc
ESL .... Extreme sea level
EU .... European Union
FRMP .... Flood risk management plan
FRR .... Flood risk review
FSR .... Flood studies report
FSU .... Flood studies update
GIS .... Geographical information system
HEFS .... High-end future scenario
HEP .... Hydrological estimation point
HPW .... High priority watercourse
HWA .... Hydrograph width analysis
IBIDEM .... Interactive bridge invoking the design event method
ICPSS .... Irish coastal protection strategy study
ISIS .... One-dimensional hydraulic modelling software
LA .... Local authority
LIDAR .... Light detection and ranging
MPW .... Medium priority watercourse
MRFS .... Mid-range future scenario
OPW .... the Office of Public Works
PFRA .... Preliminary flood risk assessment
Q(T) .... Flow for a given return period
QMED .... Median annual flood, used in FSU methods
RBD .... River basin district
T .... Return period, inverse of AEP
Tp .... Time to peak
TUFLOW .... Two-dimensional hydraulic modelling software
UoM .... Unit of management
WP .... Work package

1 Introduction

1.1 Background

This report describes the hydrological analysis carried out as part of the Catchment-Based Flood Risk Assessment and Management Study (CFRAM) for the Western River Basin. The Inception report, issued in 2012, presented an initial hydrological analysis including a detailed review of rainfall and flood event data and development of a method statement. This hydrology report is intended to be readable with minimal need to refer back to the Inception report. However, not all the hydrological analysis presented in the Inception Report is repeated here.

1.2 Objectives of hydrological study

The brief calls for a comprehensive and detailed hydrological analysis that places particular emphasis on flood flow estimation for the main flood risk areas (termed AFAs, Areas for Further Assessment) and the watercourses that flow through these areas (termed HPWs, High Priority Watercourses).

The principal objective of the hydrological study is to derive best estimates of design fluvial flood parameters including peak flows, hydrographs, flood volumes and other design flood parameters, as necessary to deliver the requirements of the CFRAM project, for all Hydrological Estimation Points (HEPs). The study also includes derivation of design coastal flood parameters for AFAs subject to significant coastal flood risk.

1.3 Report structure

Chapter 2 describes the physical characteristics of the study area that are relevant for flood hydrology. Chapter 3 summarises the hydrometric data that have been used in the study. The method statement in Chapter 4 sets out an overview of, and justification for, the choice of analysis method. Chapters 5 and 6 describe the core of the hydrological study, the estimation of design peak flow and design hydrograph shapes. Some of the analysis in Chapters 5 and 6 is described in terms of the entire Western CFRAM study area, since the comparisons of methods were carried out using example sites throughout the Western river basin district. Towards the end of each chapter, the text focuses more specifically on UoM 29. Chapter 7 summarises the approach that has been taken for design flow estimation at each AFA in UoM 29. The remaining chapters deal with application of the flows to the river models, uncertainty and future changes in flood flows.

Detailed results of rating reviews and analysis for individual gauging stations are presented in appendices to keep the main text more readable.

The report is intended principally for readers who understand the basic concepts of flood hydrology and have some familiarity with the methods of the Flood Studies Update.

The Hydrology Report for UoM 29 should be read in conjunction with the Hydraulic Modelling Report for UoM 29, and the specific modelling reports for each AFA, which detail the application of the hydrology to the specific river reaches.

Work on the geomorphology study that forms part of the Western CFRAM will be described in the Hydraulic Modelling Report for UoM 29, as will the assessment of the joint probability of fluvial and coastal flooding.

1.4 Unit of management 29 - Galway Bay South East

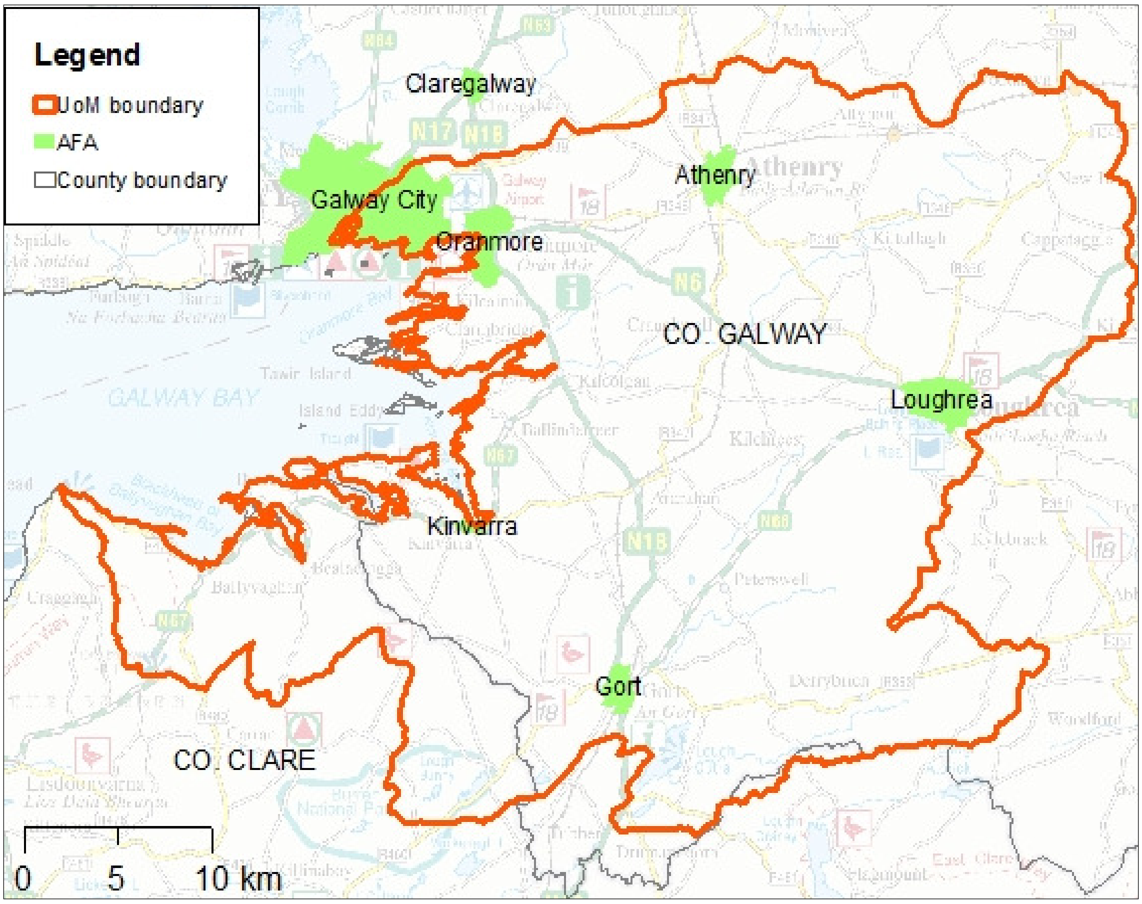
Unit of management 29, also referred to as Galway Bay South East, covers an area of 1,270 square kilometres of the Western RBD. The area is predominantly within County Galway but there are also some small areas of County Clare included. The main settlements in this UoM are:

- Loughrea
- Oranmore
- Athenry

- Gort

Parts of eastern Galway City are also included in UoM29 but for the CFRAM study the Galway City AFA is included in UoM30, covering the Corrib catchment.

Figure 1-1: Unit of management 29: Galway Bay South East - overview map



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The Flood Risk Review identified five Areas for Further Assessment (AFAs) in UoM 29. These are:

1. Athenry (situated within the Clarinbridge watercourse catchment)
2. Gort (situated within the Gort/Cannahowna watercourse catchment)
3. Kinvarra (Coastal)
4. Loughrea (situated within the Kilcogan watercourse catchment)
5. Oranmore (situated within the Oranmore watercourse catchment)

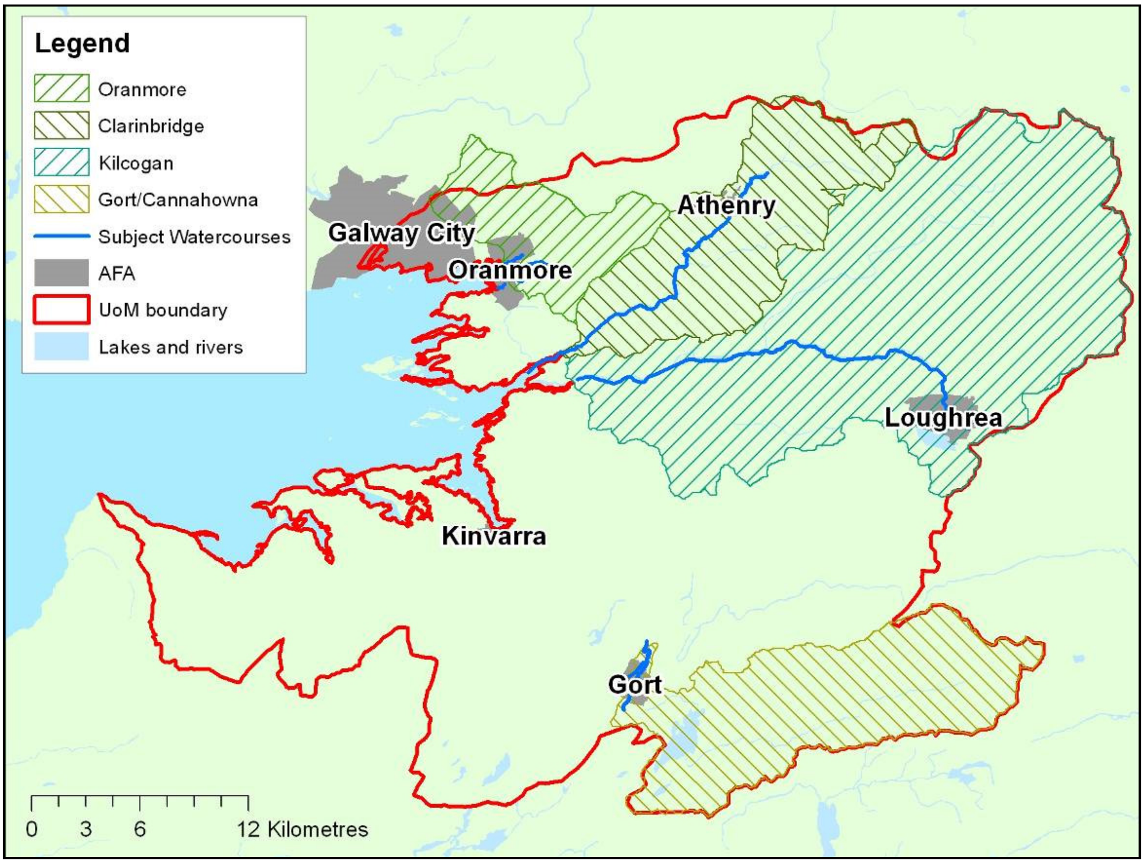
The CFRAM for UoM 29 is focusing predominantly, but not exclusively, on these five areas. At Kinvarra the flood risk is predominantly tidal and so fluvial design flows are not needed here and have been derived for the other four AFAs and associated watercourses.

2 Hydrology of the study area

2.1 Catchments

The unit of management consist of a number of catchments, each draining into Galway Bay. The CFRAM study includes reaches within four of these catchments; therefore it is these which are described below. The catchment boundaries are shown in Figure 2-1 below and are provided in the digital deliverables, Section 12. Further details of the geology, soils and land use within the catchments can be found in the WCFRAM Strategic Environmental Assessment Scoping Report[1] and further details of each specific watercourse can be found in the WCFRAM Hydraulic Modelling Report for UoM 29.

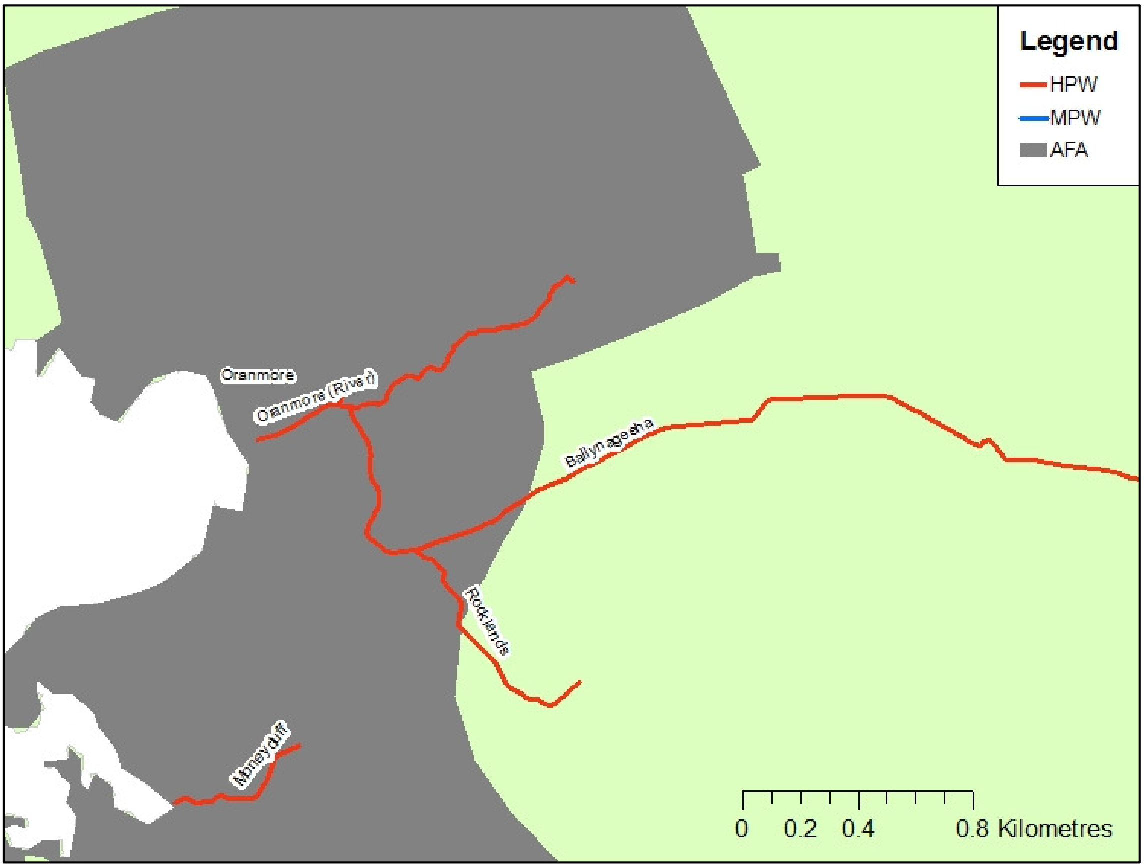
Figure 2-1: Subject catchments in UoM29



[1] JBA Consulting (2013), Western River Basin District Catchment-based Flood Risk Assessment and Management (CFRAM) Strategic Environmental Assessment, Scoping Report, Office of Public Works.

2.1.1 Oranmore

Figure 2-2: Oranmore AFA Watercourses



The Oranmore catchment is the smallest included within the UoM 29 study area, with a catchment area of 57 km^2 (only around 4% of the UoM topographic area). The Oranmore watercourse flows through the town of Oranmore and is joined in the town by a tributary, Ballynageeha. The catchment includes the Galway Airport area. The watercourse rises north of Oranmore around the Kiltullagh area and the average gradient of the catchment (S1085) is 1.33m/km, which is low. The northern boundary of this catchment is a little uncertain given the presence of Kiltullagh Turlough. It is thought that this additional catchment area, shown in Figure 2-1 outside of the UoM boundary, will drain to the Oranmore catchment; digital terrain data shown the topography of the area sloping south east toward Oranmore.

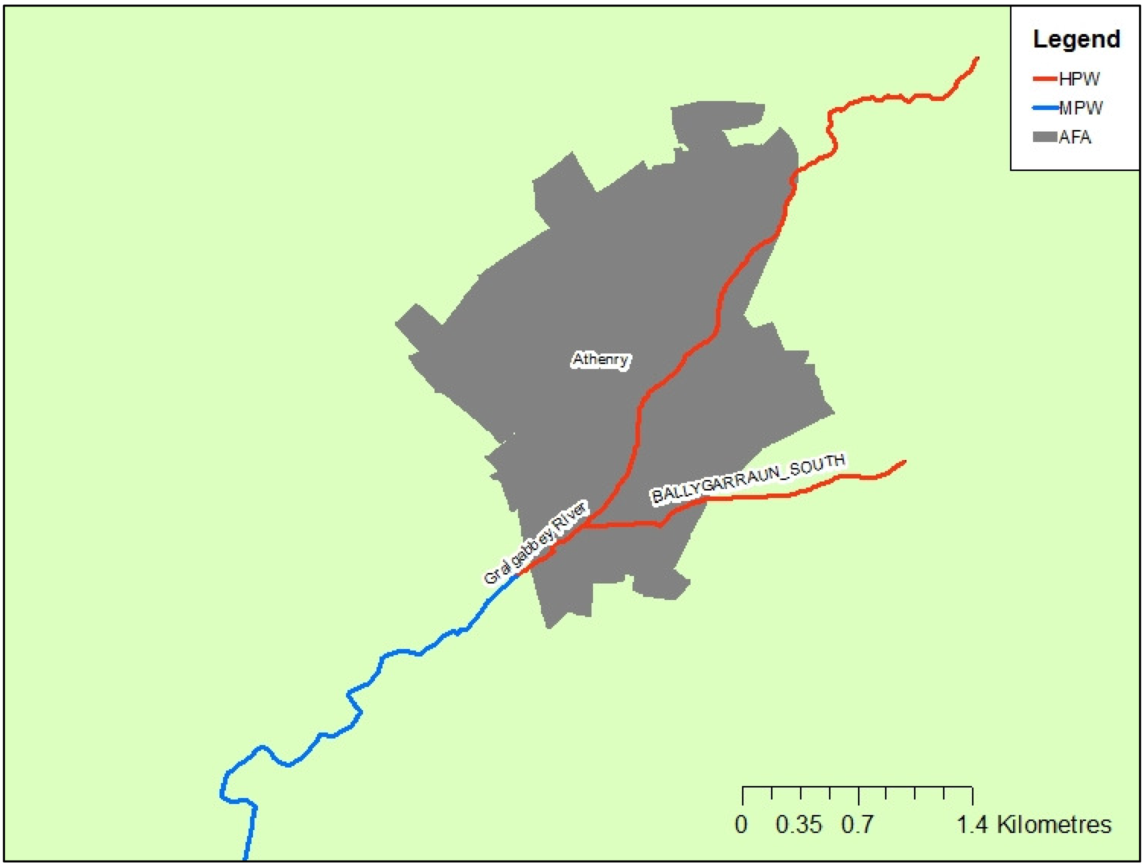
Mean annual rainfall for Oranmore is 1080mm.

UoM 29 is almost entirely underlain by karstic Carboniferous Limestone with soils predominantly comprised of deep, well drained minerals. The BFIsoil value of 0.63 at Oranmore indicates moderately permeable soils.

There are no significant permanent lakes present within the catchment.

2.1.2 Clarinbridge

Figure 2-3: Athenry AFA Watercourses



A catchment significantly larger than that of the Oranmore, the Clarinbridge has a catchment area of 116 km^2 in total (around 9% of the UoM) and 47 km^2 to the downstream limit of the AFA. The watercourse flows through the AFA of Athenry and discharges into Galway Bay at Kilcornan. As it flows through Athenry the watercourse is known as the Graigabbey River, changing to the Lavally River and subsequently the Clarinbridge before its mouth. The study reach is approximately 19km in length. The watercourse rises north east of Athenry around the Attymon area. The catchment is fairly low-lying, with a high point of around 110m. The OPW supplied catchment boundary north of Athenry differs slightly from the UoM boundary; digital terrain data suggest the supplied catchments are correct.

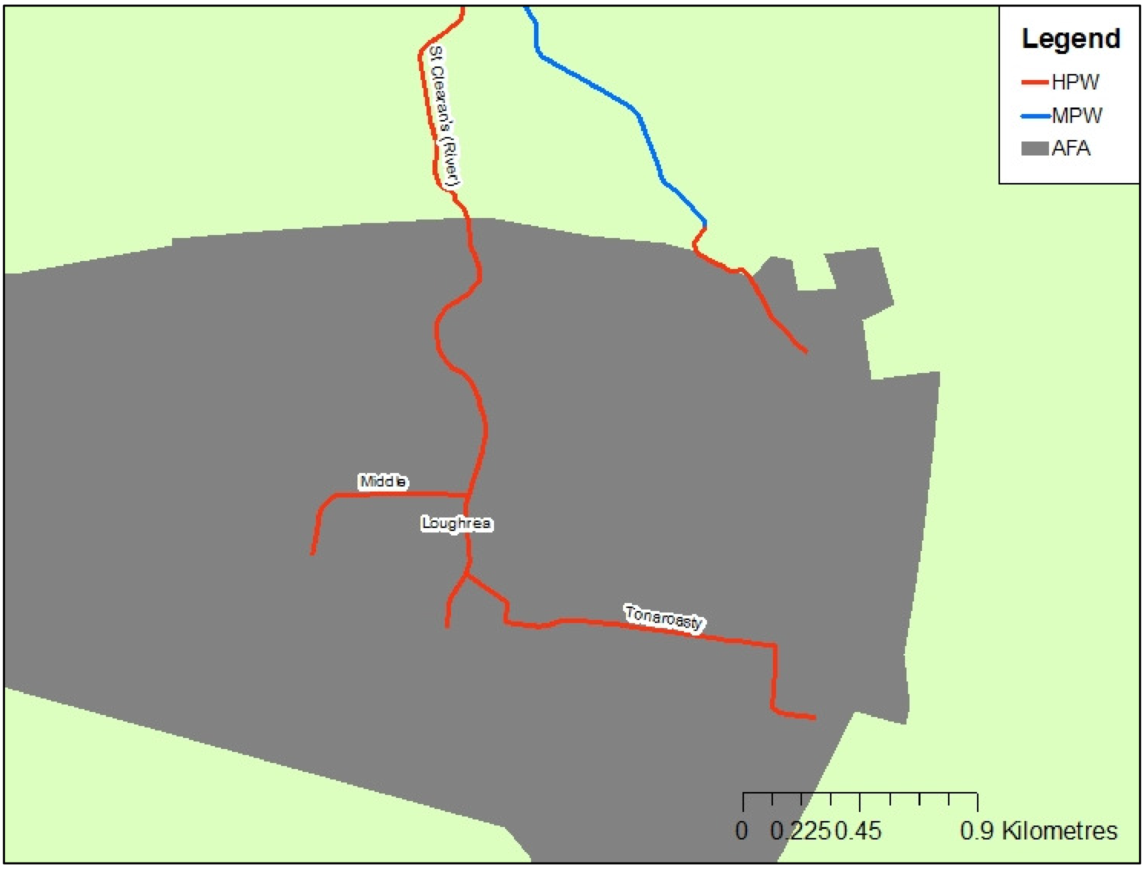
The mean annual rainfall for the catchment is 1100mm, and is similar to the Oranmore catchment. The mean annual rainfall to the downstream limit of the AFA is 1200mm.

The geology and soils of the Clarinbridge catchment are very similar to those of the Oranmore and the BFIsoil value of 0.62 indicates moderately permeable soils.

There are no significant permanent lakes present within the catchment.

2.1.3 Kilcogan

Figure 2-4: Loughrea AFA watercourses



The Kilcogan catchment is one of the larger catchments in UoM 29, with a total contributing area of 354 km^2 (28% of the UoM) and 17 km^2 to the downstream limit of the AFA. In its upper reaches the Kilcogan watercourse is known as St Clearan's. The catchment drains east to west from Loughrea to Galway Bay. There are many tributaries in the Loughrea area including St Clearan's North and the Tullagh. Further downstream major tributaries are the Craughwell River and the Dooyertha River. The study reach is approximately 25km long. The headwaters of the river are found around Loughrea. A number of small contributing tributaries flow into Lough Rea in this area. The average catchment gradient is a relatively shallow 1.83 m/km.

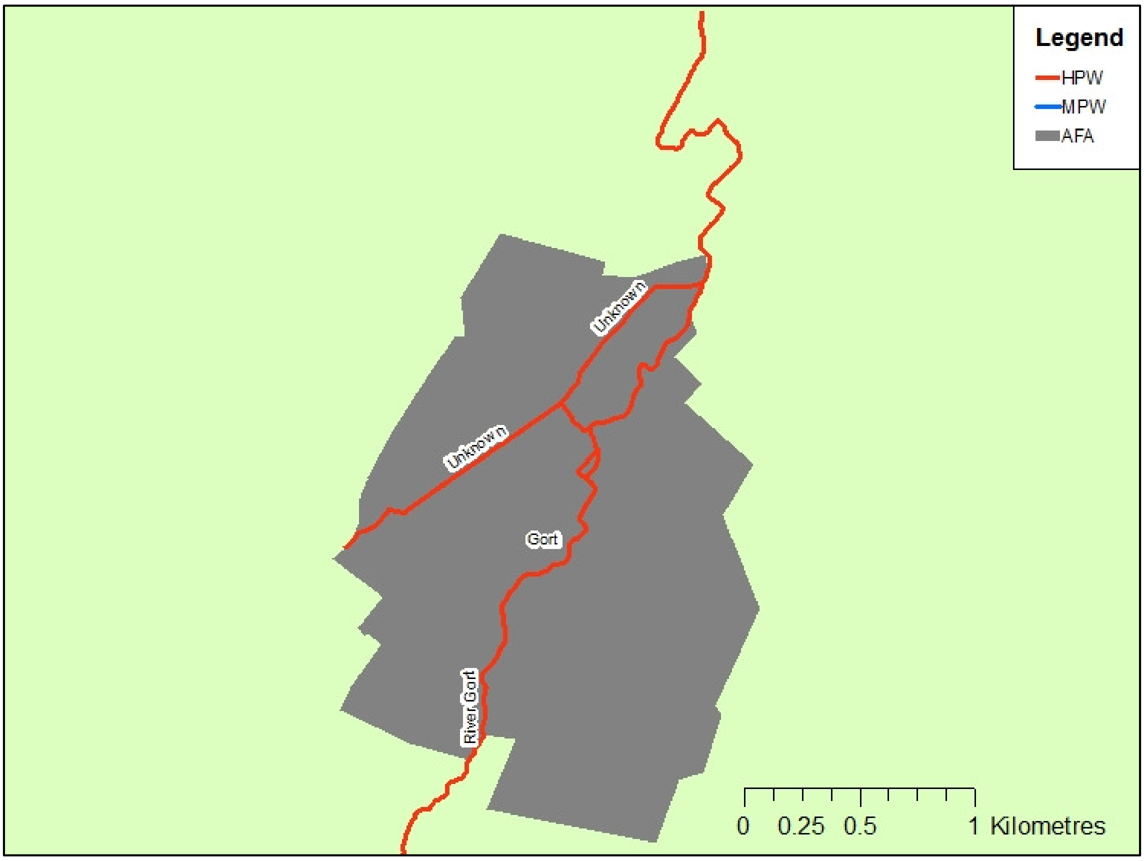
As with the Oranmore and Clarinbridge catchments, mean annual rainfall is 1080mm. The mean annual rainfall to the downstream limit of the AFA is 1130mm.

The geology and soils of the Kilcogan catchment are very similar to those of the Oranmore and Clarinbridge, although there is an area of peat and deep poorly drained minerals in the upper catchment. The BFIsoil value of 0.63 indicates moderately permeable soils.

There are a number of lakes present in the catchment, including Lough Rea, although their influence on flood flows is minor at the downstream limit, as evidenced by a FARL value of 0.98.

2.1.4 Gort/Cannahowna

Figure 2-5: Gort AFA watercourses



The Cannahowna catchment is located in a very karstic area. The watercourse is also known as the Gort River as it flows through the town of Gort, and the Beagh River further upstream.

The topographic catchment upstream of Gort has an area of 136km². The watercourse rises to the east of Gort in the Slieve Aughty hills. The high point of the catchment is Cashlaundrumlahan at 359m.

The Slieve Aughty range is largely Old Red Sandstone, which does not support significant groundwater flow. To the west of the hills, approaching Lough Cutra, the geology changes to Carboniferous Limestone. This is initially the Tournaisian group and then, downstream of Lough Cutra, the karstified Visean limestone (see Figure 2-6).

Four kilometres downstream of Lough Cutra the river flows into a swallow hole, called the Punch Bowl. A kilometre to the west is Cannahowna Rising where the river re-emerges, flowing north towards Gort. The hydrology of the watercourse thereafter is described in Trinity College Dublin's recent report on groundwater flood risk from turloughs[2]; after flowing through Gort, the river sinks again at Polltoophill (Castletown) sink. From here, the river flows towards Polldeelin rising via a 2.4km long underground conduit, sinking 62m below ground level before re-emerging at a spring to the west of the N18 at Kiltartan along with the combined flow from two other catchments. From here flow is over-ground for around 500m before sinking at the Kiltartan Sink, only to rise again 400m to the west as the Coole River. From there on flow is via a chain of turloughs, eventually discharging to the sea via large springs in the inter-tidal zone at Kinvarra.

This CFRAM study covers fluvial and coastal flooding. It does not consider flooding that occurs directly from groundwater sources, such as turloughs, as this is being modelled separately in the above mentioned project, being carried out by Trinity College Dublin. This CFRAM report covers

[2] Naughton, Owen (2013). Assessment of groundwater flooding risks posed by turloughs. Site assessment report – Gort Lowlands, Co. Galway. Report by Trinity College Dublin for OPW.

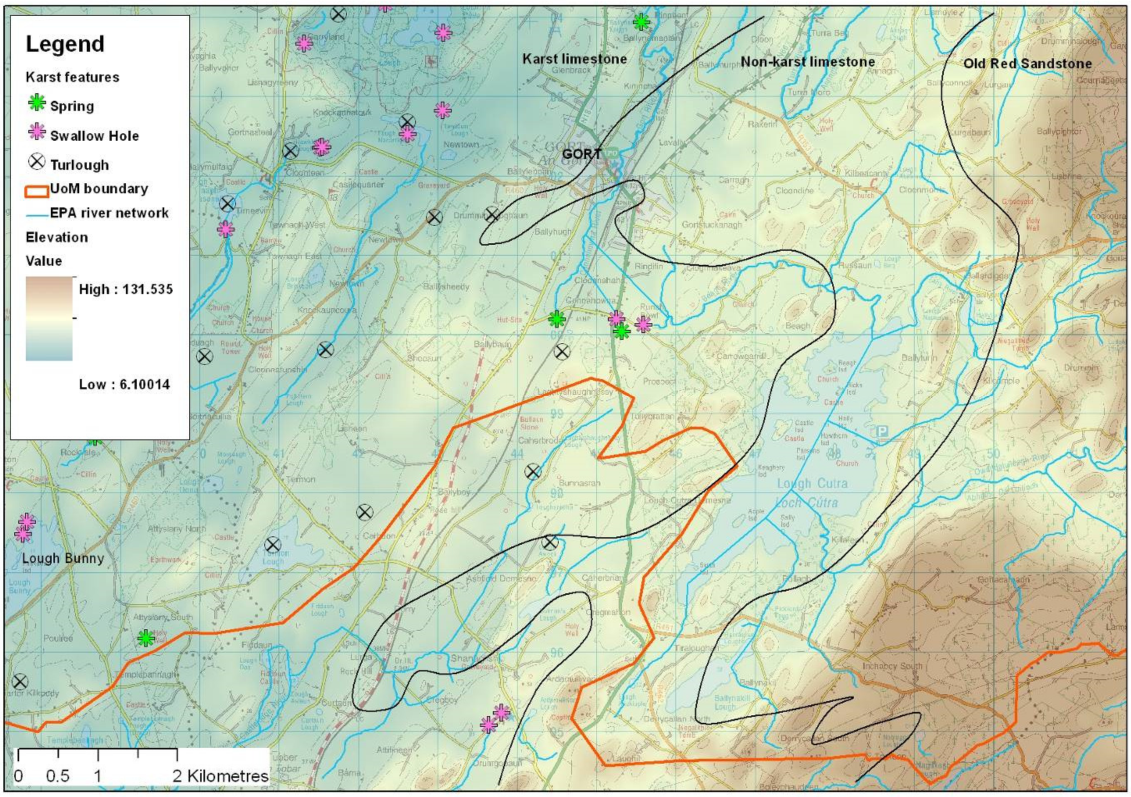
just a short stretch of the Gort River, around the town of Gort, rather than extending down the river to the sea as on other catchments.

Soils in the catchment draining to Gort are primarily deep well drained minerals, with some areas of peat and deep, poorly drained minerals in the upper catchment. The BFIsoil value of 0.61 indicates moderately permeable soils.

Mean annual rainfall for the catchment is slightly higher than the other catchments, at 1200mm.

There are a number of large lakes present in the catchment, the most significant being Lough Cutra, resulting in a FARL value of 0.82 at Gort. There is a large area of forestry in the upper catchment.

Figure 2-6: Karst features and geology around Gort



2.1.5 Maps of selected catchment descriptors

The maps below show how catchment properties vary across the unit of management. Each point indicates the properties of the catchment draining to that location. The FSU research derived values of catchment descriptors at 500m intervals along flow paths for all catchments draining an area of at least 1km^2.

No catchment descriptors are shown for much of the south-western area of the unit of management, where there are no surface watercourses as the drainage is predominantly via underground karst features.

Figure 2-7: Standard-period annual average rainfall, SAAR

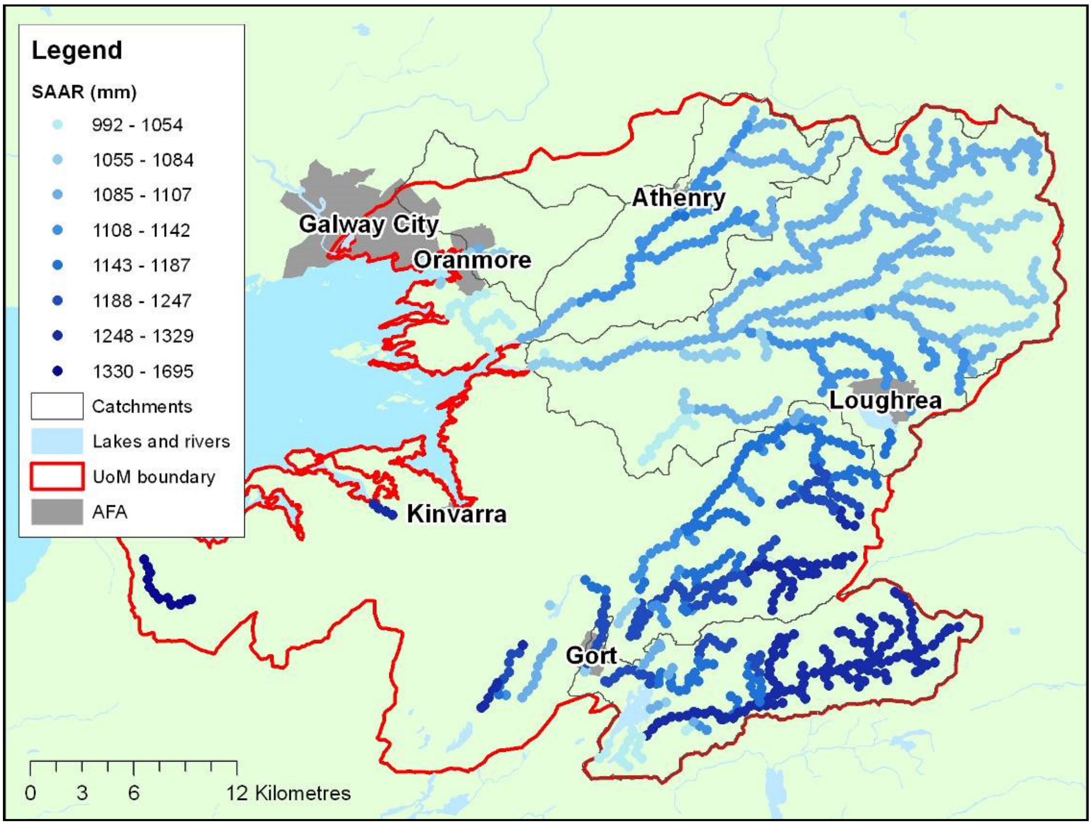


Figure 2-8: Baseflow index estimated from soil properties, BFIsoil

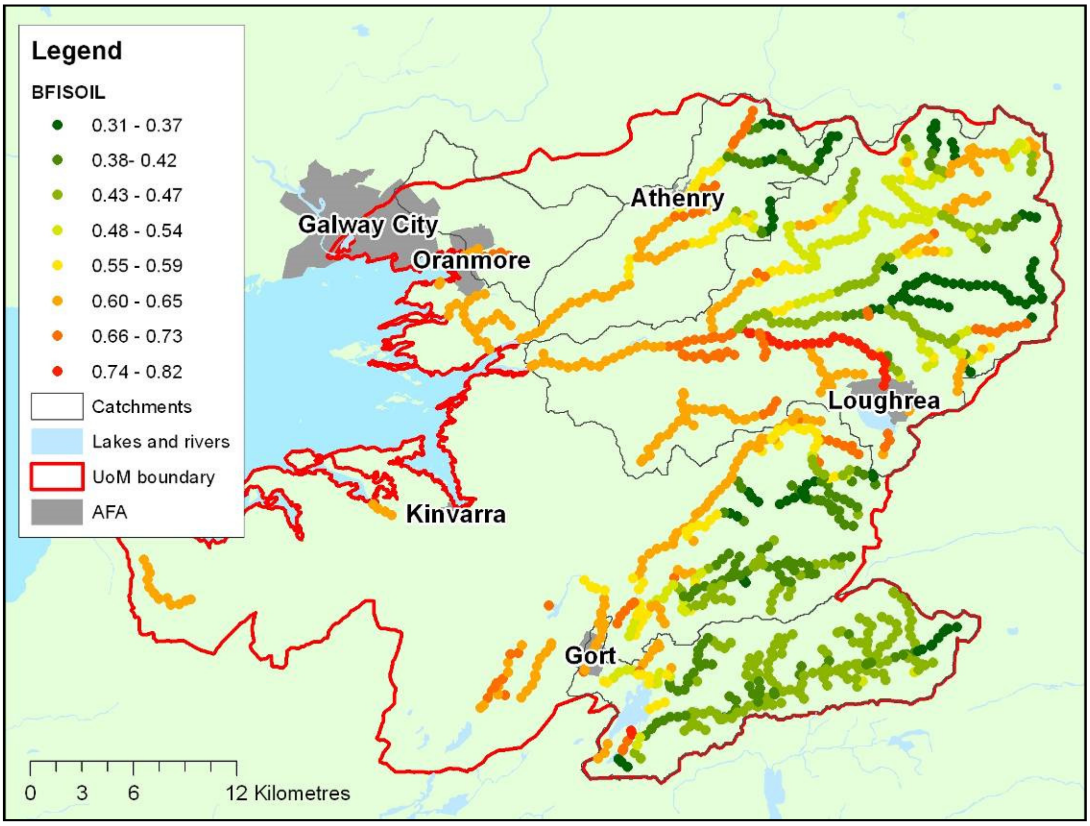


Figure 2-9: Slope of the main watercourse in the catchment, S1085

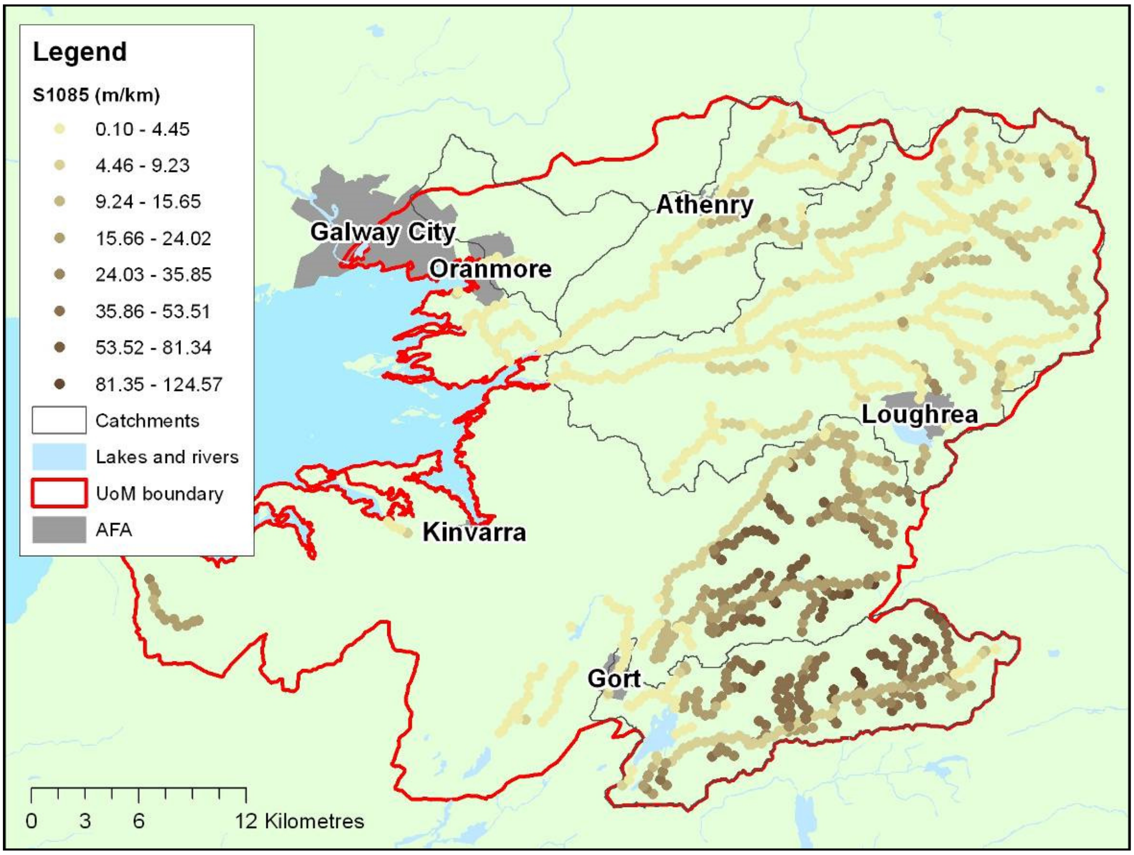
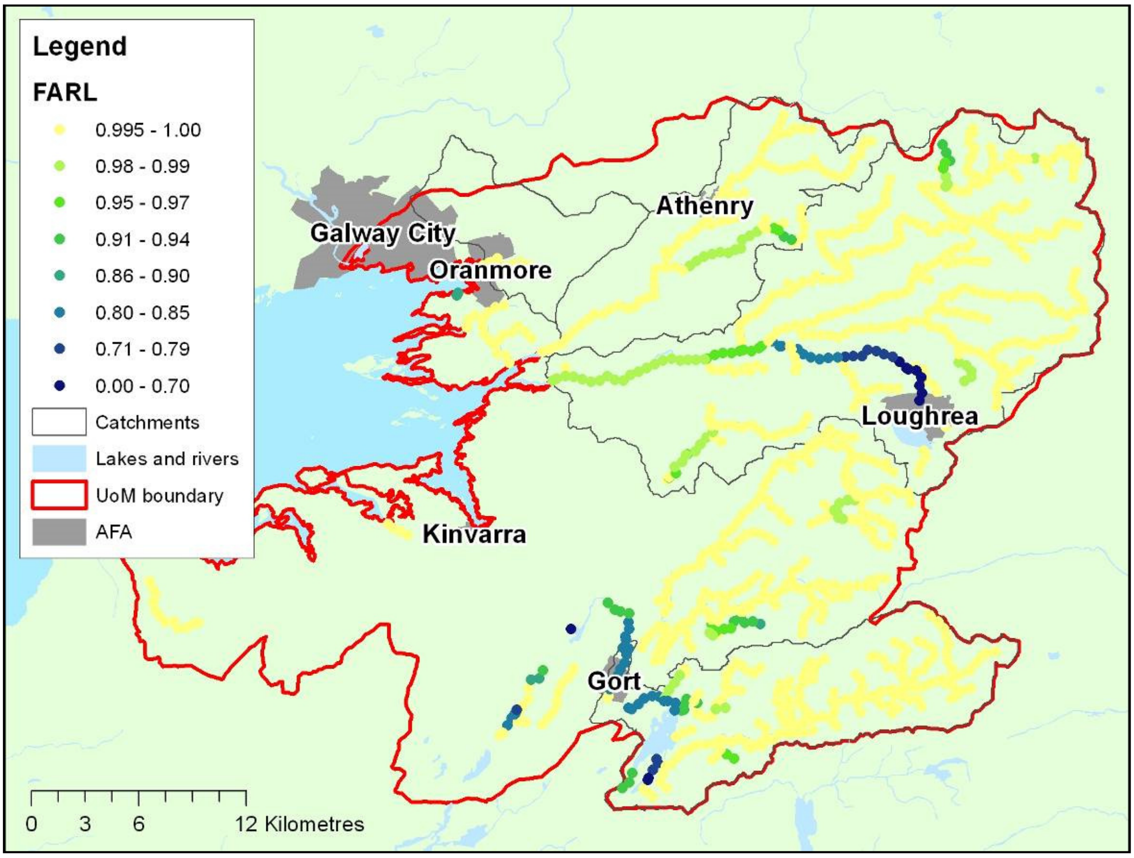


Figure 2-10: Flood attenuation by reservoirs and lakes, FARL



3 Hydrological data

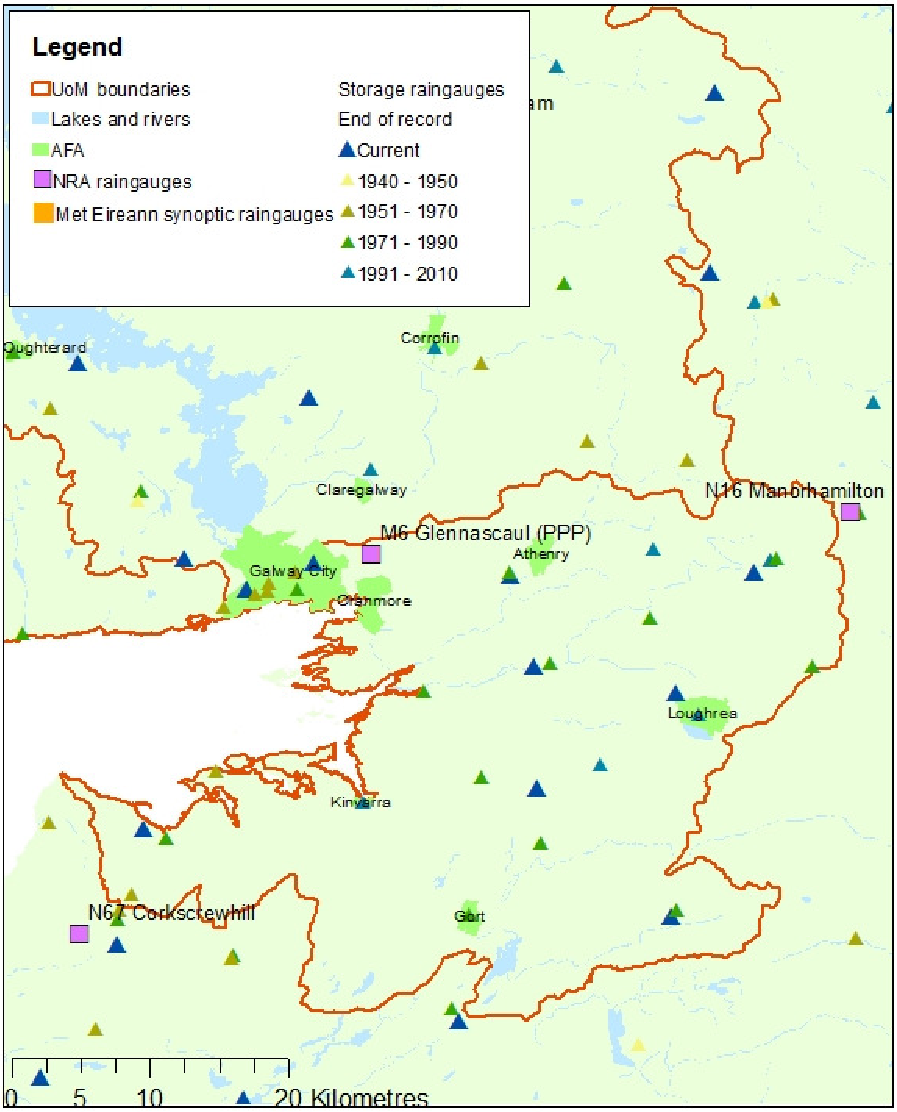
3.1 Meteorological data

Figure 3-1 shows raingauges (past and present) for which digital data is available from Met Éireann within this unit of management. All the gauges are storage gauges, mostly read once a day. There are no recording raingauges (which can measure sub-daily rainfall) in the vicinity of UoM29. The closest is at Gurteen which is 54km east of Gort.

Some of the gauges have digital data available from the 1950s. Analysis of the rainfall data, from synoptic sources, tipping bucket gauges and storage gauges, is described in Appendix G (taken from the Inception Report) and in Section 6.3 which describes lag analysis. This analysis from the inception phase has not been carried forward into the main phase study for UoM29.

Additional rainfall data is collected by the National Roads Authority using rainfall sensors, including at a sensor on the edge of UoM 29 by the M6 near Galway Airport. Information on this dataset was provided after completion of the inception phase and so it has not been incorporated in the analysis of rainfall events.

Figure 3-1: Raingauge locations

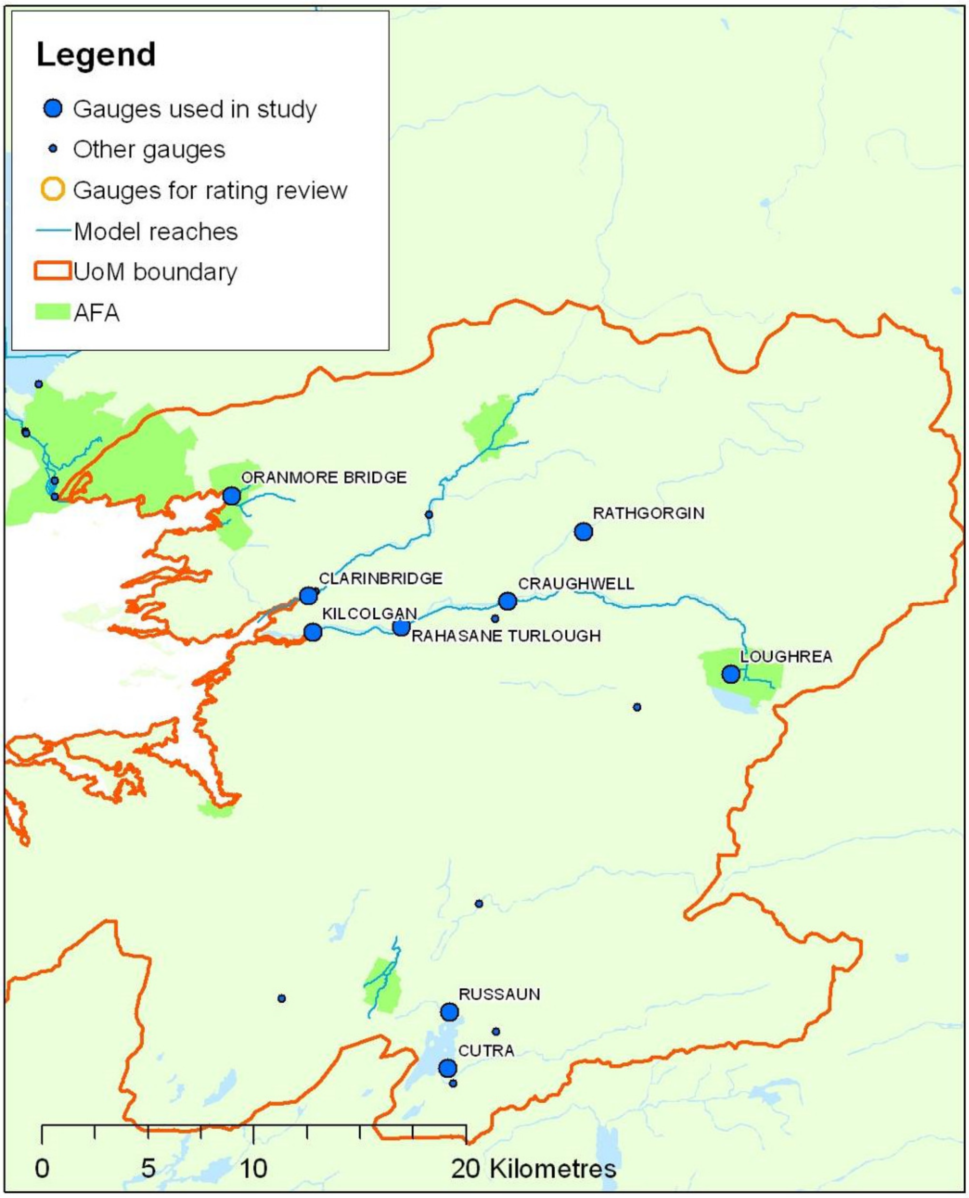


3.2 Fluvial data

Figure 3-2 shows the river gauging stations in the catchments where AFAs have been identified within this unit of management. It shows only those stations at which a continuous record of river level is available, excluding staff gauges where occasional readings are taken. It includes closed gauges as well as current ones. In total, there are nine river level gauges that have been judged as potentially useful for this study, i.e. either on rivers that are to be modelled or nearby with good quality flood peak datasets that represent potential pivotal sites. Two of these gauges (Russuan – 29009 and Cutra - 29071) are close together and are used jointly to calculate flow, so the effective number of gauge sites is eight.

At six of these gauges it is possible to calculate flow from the observed water levels using a rating equation. None of the gauges have been identified for review and extension of rating equations within this study. The 'Other gauges' shown on the map will be used in the development of pooling groups.

Figure 3-2: River gauge locations



Summary information on the gauges and their relevance to this study is given in Table 3-1. River level and flow data has been provided for all these gauges by the OPW and EPA.

Table 3-1 Summary of river level and flow gauges

Ref. No.	Name	Catch-ment Area (km^2)	Start of record	End of record	Flow available ?	FSU class	Comments
29001	RATHGORGIN	116	1957	-	Yes	A1	AMAX data available from 1957, flow data began in 1961
29002	RAHASANE TURLOUGH	332	1970	-	Yes	Due to unquantifiable amounts of flow that bypass the station, both overground and underground, this site was unsuitable for inclusion in the FSU.	
29004	CLARINBRIDGE	123	1973	-	Yes	A2	29014, Caherfinesker, is closer to the AFA but has no reliable rating for high flows.
29007	CRAUGHWELL	272	1983	-	Yes	B	
29009	RUSSAUN	124	2001	-	No	n/a	See note 3 below.
29011	KILCOLGAN	354	1983	-	Yes	A1	Some tidal influence at lower flows
29015	ORANMORE BRIDGE	58	1982	-	No	n/a	Largely tidal, with little fluvial influence.
29070	LOUGHREA	12*	1976	1992	No	n/a	
29071	CUTRA	124	1976	-	Yes	A2	See note 3 below.

*From supplied hydrometric data register only

Notes:

1. The start of record is given as the earlier of either the year from which continuous digital data is available or the year from which flood peak data are available. Some gauges have earlier records available on paper charts.
2. FSU quality classes indicate the extent to which high flow data can be relied on as judged by the Flood Studies Update research programme. Class A gauges are thought to provide reasonable measurement of extreme floods, and thus are suitable for flood frequency analysis (the best gauges being classed as A1); class B are suitable for calculation of moderate floods around QMED and class C have potential for extrapolation up to QMED. Class U indicates gauges thought to be unsuitable at the time of the FSU research. These quality classes were developed around 2005-2006 and some may no longer be applicable following recent high flow gaugings.
3. The gauges labelled Russuan and Cutra are effectively treated as one site for flow measurement: the level of Lough Cutra, measured at the Cutra gauge, is used to calculate the outflow from the lough at Russuan using a rating equation developed from flow gaugings carried out at Russuan.
4. All gauges with flow available have rating equations and check gaugings. All gauges listed have annual maximum series.
5. All gauges are operated by OPW apart from Loughrea and Cutra which are operated by Galway County Council.

The flow data at the gauges are regarded as fit for purpose, apart from where stated in the table above.

Not one of the four AFAs for which design flows are needed has a flow gauging station on site. There are level gauges at Oranmore and Lough Rea. Athenry, Loughrea and Gort have flow data available either further downstream or upstream on the same watercourse:

- Around 12km downstream of Athenry there is a gauge at Clarinbridge. It has good quality peak flow data available from 1973. However, the catchment at Clarinbridge is several times larger than that at Athenry.
- Around 14km downstream of Loughrea there is a gauge at Craughwell which provides reasonable quality flood peaks from 1983. The catchment at Craughwell is very much larger than that at Loughrea, and flows at Loughrea are likely to be heavily influenced by

the attenuation effect of Lough Rea, so flow data at Craughwell is unlikely to be helpful in estimation of design flows at Loughrea.

- 4-5km upstream of Gort there is a gauging station which measures the outflow from Lough Cutra. Water flows out of the lough into the Beagh River which, after 3.5km, flows into a swallow hole, the Punch Bowl. The underground stream re-emerges 1km to the west, upstream of Gort at the Cannahowna Rising. As discussed above, the Lough Cutra gauge may be usefully located for measuring the flow through Gort if it gives an accurate indication of flow down the swallow hole.

Thus there are some data gaps associated with the hydrometric network. For any future improvements to the design flood estimates it would be useful if a flow gauging station could be established at Athenry and Loughrea. At Oranmore it may be that flood risk is predominantly tidal but if modelling shows there is a significant hazard from fluvial flooding, it would be possible to estimate future design flows with more confidence if a flow gauge could be established at a site free from tidal influence.

3.3 Review of rating equations

No gauges in UoM 29 have been identified for review of rating equations within the CFRAM study. For consistency with the appendix numbering system in reports on other UoMs, Appendix A has been set aside to record the results of rating reviews, but in the case of UoM 29 the appendix contains no material.

3.4 Tidal data

Figure 3-3 and Table 3-2 detail the location and available data associated with tidal gauges around the west coast of Ireland. Many of these gauges have been recently installed and are part of an ongoing project to develop a centrally controlled Irish national tidal network.

Due to the large distances between the gauges within the Western CFRAM study area and the short timeframe that data is available for, the use of this data for the purposes of calibration will be limited. Where the gauge is located at the AFA (Galway and Sligo) and there is a tidally influenced gauge located on the watercourse there will be good confidence in the suitability of the gauge data for the site. Where the AFAs are situated between gauges, (Ballina, Newport, Westport, Louisburgh, Clifden and Roundstone), there will be much lower confidence in data extrapolated to the AFA. The effects of the local inlets and bays on tidal levels will not be known and calibrations using this data should be treated with caution.

Figure 3-3: Tidal gauge locations

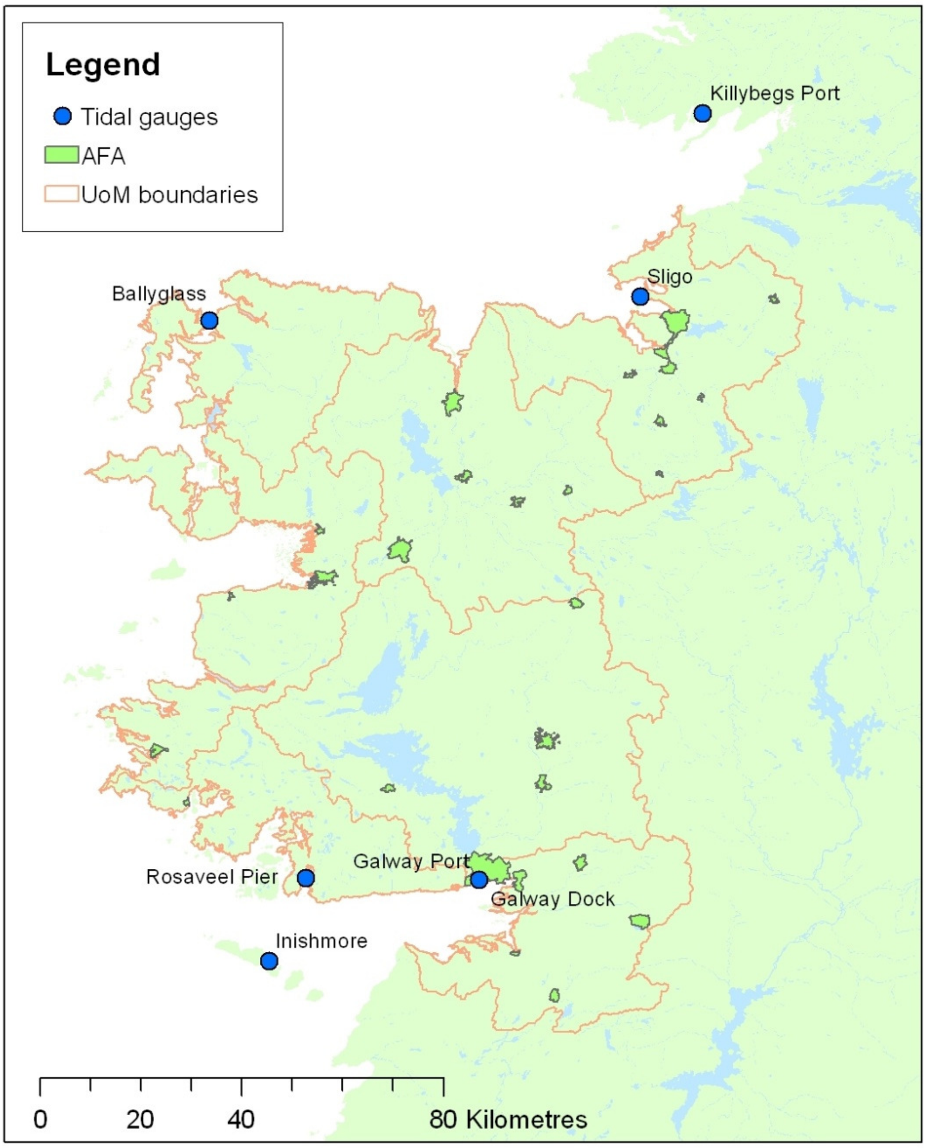


Table 3-2 Summary of tidal gauges

Name	Operating Authority	Start of record	End of record	Comments
Killybegs	Marine Institute	Mar 2007	-	
Sligo, Rosses Point	Marine Institute	Jul 2008	Aug 2013	
Ballyglass	Marine Institute	Apr 2008	-	
Inishmore	Galway Co. Co.	Apr 2007	-	Currently inactive due to harbour works
Rosaveel Pier	OPW	Jul 1986	-	
Galway Port	Marine Institute/Galway Port Company	Mar 2007	-	
Galway Dock	OPW	Sep 1985	Nov 1989	

3.5 Historical flood data

Information on historical flooding is helpful in developing an understanding of flood risk in the area and can help guide the estimation of design flows.

Only limited information with any indication of the magnitude and/or extent of historic flooding was available for UoM29. The following sources of information were used for the investigation of historic flooding:

- Irish Newspaper Archives (www.irishnewsarchive.com). The search included newspapers such as Irish Independent 1905 - 2011, Irish Press 1931 - 1995, Freemans Journal 1763 - 1924, Tuam Herald 1837 - 2000, Sunday Independent 1905 - 2011, Connacht Tribute 1909 - 2011.
- Hickey, K. (2010) Deluge. Ireland's weather disasters 2009-2010. MPG Books, Bodmin.
- A flood chronology for the Western River Basin District compiled by Kieran Hickey of Dept of Geography, NUI Galway, for the purposes of this study.
- Archer, D. (2011) Northern Ireland flood chronology. Personal communication.
- Database of historical weather events (http://booty.org.uk/booty.weather/climate/wxevents.htm)
- Local history websites and books.
- Previous flood studies for the area.
- Papers published in journals or presented at conferences.
- Reports and flood outlines available on www.floodmaps.ie.
- Information provided by local authorities during the flood risk review.
- Hydrometric data, in particular long-term flow and rainfall records

Most of these sources can be regarded as good-quality datasets, although any anecdotal information, particularly if it has been gathered some time after the flood event, has been treated with appropriate caution.

Analysis of the historic information is described in Section 5.2.

4 Method statement

The general approach followed for estimating design flows in this unit of management was developed during the inception stage. This chapter of the report sets out the thinking behind the methods that have been chosen, focusing on the nature of the catchments (described in Chapter 2); the data available (described in Chapter 3) and the needs of the study (described below).

4.1 Needs of the study

The specification calls for estimation of design flood parameters for eight AEPs, ranging from 50% to 0.1%.

Estimation of design groundwater conditions is not required, as groundwater flood mapping is being covered in a separate nationwide study. However, in karst areas such as much of this unit of management, there is not always a distinct boundary between fluvial and groundwater flooding. Some rivers are affected by outflows from or inflows to underground karst systems. The ongoing groundwater flood mapping study is expected to include refinement of the previous karst flow modelling studies carried out in the Gort to Ardrahan area, and this may yield outputs that are useful for informing fluvial flood estimation. The method statement below will be refined once the groundwater flooding study has made further progress.

Design flows are needed for hydrological estimation points (HEPs) in four of the AFAs:

- The Oranmore and Ballynageegha Rivers at Oranmore. Refer to Figures in Section 2.
- The Graigabbey River at Athenry. Refer to Figures in Section 2.
- St Clearan's River and a small tributary at Loughrea. Refer to Figures in Section 2.
- Cannahowna/Gort River at Gort. Refer to Figures in Section 2

At the fifth AFA, Kinvarra, there are no surface watercourses and so no design flows are required.

There are no watercourses in the part of Galway City which lies inside UoM29.

The specification calls for HEPs to be located upstream, downstream and centrally at each AFA and at all gauging stations. Points must also be located upstream and downstream of tributaries contributing more than 10% of flow in the main channel with no greater spacing than every 5 km. These guidelines have been followed wherever possible when locating these points, in addition to adding a point wherever the catchment area increases by 10%.

However, in certain locations the guidelines have been adapted. For example, until the hydrological analysis is undertaken it is not possible to ascertain which tributaries contribute 10% of main channel flow; therefore HEPs have been located on tributaries that contribute greater than 10% of catchment area. Elsewhere it may be the case that the location of a point at the upstream extent of the AFA is not necessary, when another point is located nearby (i.e. at a tributary confluence). It is also not practical to add a flow estimation point everywhere the catchment increases by 10% on very small tributaries - this would result in an unmanageable number of points. Where this is the case a minimum point spacing of 400m has been employed (this has superseded the 200m spacing proposed in the Inception Report as initial results highlighted no significant change in design flows on these small watercourses at this spatial scale).

The locations and catchment boundaries of HEPs are included as ArcGIS shapefiles within the digital deliverables from the Western CFRAM project, Section 12.

Catchment boundaries for each HEP have been obtained from the information supplied by the OPW (which were derived for implementation of the Water Framework Directive). These have been checked using Arc Hydro, as described in the Inception Report. Catchment descriptors for each HEP were obtained from the FSU datasets, with adjustments made where catchment boundaries were in error, again as described in the Inception Report.

4.2 Choice of method

The combination of unusual catchments and an absence of nearby reliable flood peak series for most AFAs makes for challenging flood estimation in this UoM. As a result, it is necessary to accept high levels of uncertainty at some locations.

The presence of extensive areas of karst limestone in the region has a number of implications for flood estimation:

- The drainage network may not follow the topographic catchment, and could be fed by underground watercourses which are not constrained by the overground catchment profiles. There is greater uncertainty regarding catchment boundaries and therefore also area and other catchment descriptors.
- Flows are unlikely to increase smoothly moving downstream (in relation to increases in upstream catchment area). Rather, streams may locally gain or lose volume depending on the underlying character of the karst. This behaviour may change seasonally and depends on the groundwater table position. This means that use of pivotal gauges to adjust flow estimates for ungauged sites needs caution.
- In extreme cases, such as near Gort, entire watercourses are captured by swallow holes. This water may not re-emerge on the same watercourse, rather being transferred to a different surface water catchment.

Fortunately there is some flow data available close to Gort, which is the AFA most affected by the complexities of karst drainage.

In general, design flows have been estimated using the FSU ungauged catchment statistical method. The first iteration of design estimation involved calculation of the index flood, QMED, using catchment descriptors, with an adjustment factor derived from pivotal gauging stations. The selection of pivotal catchments for adjustment of the initial estimate of QMED is a critical part of the process and where available, priority has been given to local gauges, particularly any on the same watercourse. Having determined QMED, a growth was estimated through pooling group analysis.

In Gort the method for estimating design flows is still to be confirmed, as it will be developed iteratively through hydraulic modelling. Every effort is being made to incorporate information gleaned from the flow gauge at Lough Cutra despite its limitations noted above.

After reviewing the flood outlines produced by model runs which used the first iteration of design flows, some revisions to design flows were made in order to ensure flood levels and extents were not underestimated for the most extreme events. These revisions comprised removing the adjustment to QMED in Athenry and Oranmore where the appropriateness of donor sites was less clear. Please refer to Section 5.4 for further detail. In addition, for all HEPs, the FSR rainfall-runoff method was applied to estimate the gradient of the upper portion of the growth curve for return periods in excess of 100 years.

At Loughrea the FSU statistical approach has been applied and compared with the results of the FSR rainfall-runoff method. This is because flood flows through Loughrea are expected to be dominated by the major influence of the lake, Lough Rea, which occupies a quarter of the area of the catchment. The rainfall-runoff method has been used to estimate an inflow hydrograph to the lake, which will be routed through the lake using the ISIS hydraulic model. Full details of the development of these flows will be provided in the Loughrea Hydraulic Modelling Report.

A variety of methods for defining characteristic flood hydrographs have been tested. These included:

- Deriving a characteristic hydrograph using the parametric method from FSU Work Package (WP) 3.1, in which a hydrograph (standardised to a unit peak) is represented by a combined gamma and exponential distribution whose parameters are estimated from catchment descriptors. A potential drawback of this approach is that it can result in hydrograph durations that are not realistic given the size of the catchment.
- The above approach with parameters adjusted by reference to any nearby similar catchments for which observed flood hydrographs are available.

- The Flood Studies Report Rainfall-Runoff method, in which hydrograph shapes are determined largely by the characteristics of the catchment, i.e. time to peak and annual average rainfall.

Section 6 describes the outcome of the tests.

5 Estimation of peak flows

5.1 Descriptive analysis of flood peak and flood volume data

Analysis of flood peak data at three gauging stations (29004, 29007 and 29011) is recorded in Appendix B and summarised here. These are the gauges that have been used to estimate design flows for the study watercourses because they are appropriately located and have suitable peak flow data. Analysis at a fourth gauge, Cutra, is underway and will be reported once concerns over the flood flow rating have been addressed.

The magnitude of estimated design flows is based closely on analysis of local flood peak data where it is suitable, so it is important to develop an understanding of the statistical characteristics of the datasets. This includes testing for non-stationarity (i.e. trends or step changes) and detection and discussion of any outliers. Each gauge in the appendix is represented by a summary sheet showing a plot of the annual maximum flow series, analysis of trends and seasonality, flood frequency analysis (where the record is long enough) and summary statistics for the largest floods.

Flood records on the rivers to be modelled in this UoM date back to the mid-1970s at Clarinbridge and Cutra and from 1983 at Kilcolgan and Craughwell. A longer record is available on the Dooyertha River at Rathgorgin (a tributary of the Craughwell River), which began recording in 1961, and data from here can help set the other records in a longer-term context.

The highest flow on record at all gauges analysed, including Rathgorgin, was in November 2009. At most gauges this flood was an outlier, distinctly higher than all other events. A consequence of the outstanding magnitude of November 2009 is that its estimated annual exceedance probability (AEP) is very low: less than 0.5% at Clarinbridge and Craughwell and even lower at Kilcolgan. This was clearly an extreme event.

At Cutra the November 2009 flood, as calculated using the existing rating equation, was only marginally higher than many other events. There is a remarkable similarity between many annual maximum flows recorded here. This similarity may suggest the gauge location is limiting annual maximum flows. The EPA have indicated that there appears to be a backwater effect at very high river or groundwater levels as the river flows into a swallow hole 3 kilometres downstream of Lough Cutra, limiting capacity. This became apparent from a flow gauging carried out in November 2009, near the peak of the flood. Gauging was carried out at the Gort staff gauge, downstream of the Cutra gauge and the swallow hole. The rating curve was adjusted by EPA to account for this effect, so there is some hope that the AMAX flows give an accurate indication of the discharge at this location, even if they may not be representative of peak flows further upstream where the backwater effect is not present. However, it must be stressed that the adjusted portion of the rating is based on just one flow gauging. Additionally, it is possible that peak flows are lower at the entrance to the swallow hole where the backwater effect may be stronger. However, if it is true that the AMAX flows are representative of the discharge passing down the swallow hole then the data may in fact be quite useful for flood estimation in Gort, below the outlet from the karst system. Flows were developed using this updated EPA rating for Gort and the Gort AFA Hydraulic Modelling Report should be referred to for the final method of developing the hydrology at this site.

Floods in UoM29 appear to occur over a fairly wide season, ranging between early autumn and late winter. The record at Cutra shows floods occurring any time between August and March. At Clarinbridge annual maximum floods have occurred at all times of year.

5.2 Analysis of longer-term flood history

Records of both recent and historical floods were obtained from the sources listed in Section 3.5 and reviewed in order to provide relevant qualitative and, where possible, also quantitative information on the longer-term flood history in the area.

Information about the impacts of recent floods, including six events from the mid-1990s and November 2009 is available. For UoM29, only very limited information on floods pre-dating the gauged records was available. Pluvial flooding was reported on 21 June 1930 in Loughrea. Flooding on the road from Craughwell to Gort was reported in December 1959. The information available was often limited to only a brief notion about flooding occurring at various locations;

however, in some cases it was possible to detect the extent or magnitude, for example “5 inches of water on streets”.

There is limited potential to incorporate this historical information into a flood frequency analysis. The existing flow record at the Craughwell gauge (29007), over 10km downstream of Loughrea, includes nearly 30 years of flood peak data (from 1983) and could be used for comparison with historical events. However, the historic information does not indicate severity of the reported flooding at Craughwell and the comparison is therefore limited.

Appendix C provides a visual summary of the time line of the main flood events in UoM 29.

5.3 Overview of method for flood peak estimation

At nearly all HEPs in UoM 29, design peak flows for return periods up to 100 years have been estimated using the Flood Studies Update (FSU) method as described in research reports produced from FSU WPs 2.2 and 2.3. The exception was Loughrea where the preferred method is the Flood Studies Report rainfall-runoff method calibrated to lake level data (see Section 5.7).

The locations and catchment boundaries of HEPs are included as ArcGIS shapefiles within the digital deliverables from the Western CFRAM project, Section 12.

Because FSU methods are not fully released for general use at the time of writing, it was necessary to make some decisions about how to apply the methods presented in the reports, and to develop software to enable application of the methods. The sections below set out how the FSU methods have been applied. They have been implemented using JBA’s web-based flood estimation software, JFes, in combination with the package WINFAP-FEH which has been applied to produce single-site flood growth curves.

The FSU method for estimation of peak flows is an index flood method, involving two stages. The index flood can be thought of as a typically-sized flood for a particular catchment, and in the FSU it is defined as the flood with a 50% probability of being exceeded in a particular year. This is equivalent to the median of the annual maximum flood series, denoted QMED. The first stage of the method involves estimating QMED, and in the second stage a flood growth curve is estimated. The growth curve is a dimensionless version of the flood frequency curve which defines how the flood magnitude grows as the probability reduces, i.e. for more extreme design floods. The design flood for a particular exceedance probability is then simply calculated as the product of QMED and the value of the growth curve for that probability (known as the growth factor).

The sections below provide more detail on how each step was approached.

5.4 Estimation of QMED

The most reliable estimates of QMED are obtained directly from suitable quality flood peak data, as the median of the annual maximum series. At locations without high flow data, QMED can be estimated, with lower confidence, using a regression equation based on seven different physical catchment descriptors, in conjunction with an urban adjustment, developed in FSU WP 2.3. It is often possible to improve on this initial estimate of QMED by refining it using the process of data transfer, in which a representative gauged catchment with suitable quality data is identified and an adjustment factor for QMED calculated as the ratio of the gauged to the ungauged estimate of QMED at the gauging station. This factor is then used to adjust the initial estimate of QMED at the ungauged site, under the assumption that the factorial error in the QMED regression model is similar for two catchments. In the terminology of the FSU research reports, the gauging station where the adjustment factor is calculated is referred to as a donor site. The term pivotal site can also be used.

Some guidance on identifying suitable donor sites is given in FSU WPs 2.2 and 2.3. The WP 2.2 research compared various ways of adjusting QMED and found that the best was to select the next gauging station downstream as a donor (if available). Selecting the closest upstream gauge was also found to perform well. Selecting a more distant gauge that is similar in terms of catchment properties was found to perform less well. The report on WP 2.3 emphasises the value of locally-informed hydrological experience in selecting donors, and recommends taking into account

several factors including the degree of similarity of the subject and donor catchments, the quality of the gauged estimate of QMED and the possibility of choosing multiple donors in some cases.

For the Western CFRAM, donors have been chosen according to the following general approach:

- Where there is a gauging station on the same river as the subject site, with a comparable catchment area (up to several times larger or smaller) and no major change in physical characteristics, it has been selected as a donor.
- Where there are gauging stations upstream and downstream of the subject site, in general the adjustment factor has been calculated as a weighted average of the factor at each gauge. Weights are based on area, with more weight given to the gauge whose area is more similar to that at the subject site. Exceptions to this include situations where the downstream gauge lies below a major lough, in which case it has not been used to calculate adjustment factors for locations upstream of the lough. An example of this calculation is given below:

$$Weighted\ adjustment\ factor = \left(\frac{DS\ area - HEP\ area}{DS\ area - US\ area} \times US\ Adj \right) + \left(\frac{HEP\ area - US\ area}{DS\ area - US\ area} \times DS\ Adj \right)$$

Where
DS area = Catchment area of downstream gauge (km^2)
US area = Catchment area of upstream gauge (km^2)
HEP area = Catchment area at HEP (km^2)
DS Adj = QMED adjustment factor at downstream gauge
US Adj = QMED adjustment factor at upstream gauge

- If neither of the above apply, for example if there is no gauging station on the river or the closest gauge is a long way downstream with a catchment many times larger, then a gauging station on a nearby catchment whose characteristics (area, slope, rainfall, lough influence) are similar to those of the subject site has been chosen as a donor.
- If none of the above apply, which is often the case for subject sites on very small catchments, no donor site has been chosen and QMED has been estimated solely from catchment descriptors.

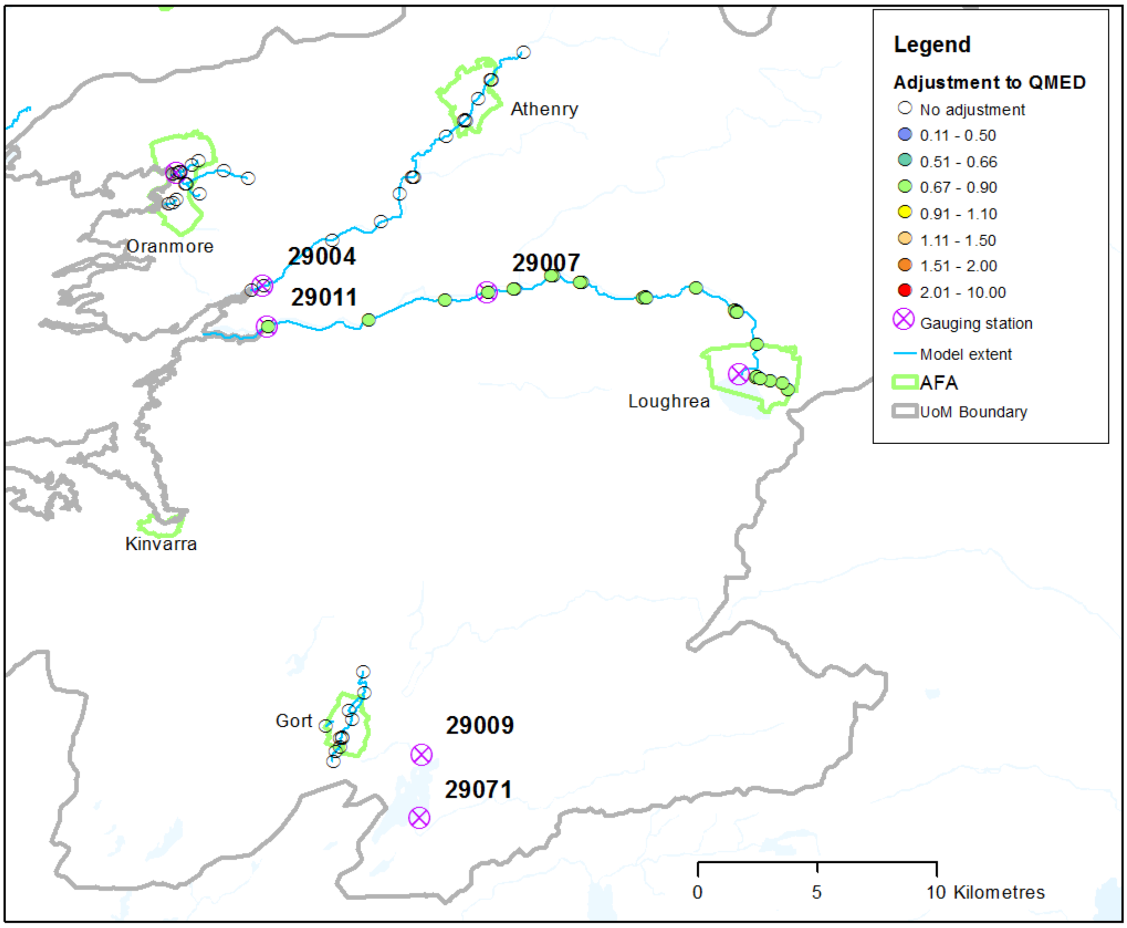
For any subject sites that are located at gauging stations, QMED has been estimated directly from the flood peak data supplied by OPW or EPA.

Some adjustment factors for QMED were removed after review of the flood outlines generated using the initial design flows. This decision was taken in cases where QMED was reduced by an adjustment factor derived from a donor site whose validity was questionable, due either to the quality of the flood peak data, the length of the record or the dissimilarity of the donor and subject catchments. In UoM 29, QMED adjustment factors were removed for Athenry and Oranmore due to the fact that the original donor site at Clarinbridge has uncertain quality data and is some distance away from both AFAs.

Figure 5-1 shows the adjustment factors for QMED both at the gauging stations (i.e. QMED from flood peak data divided by QMED from catchment descriptors) and at all the ungauged HEPs. Most gauges in UoM 29 show a reduction in QMED compared with the estimate obtained from catchment descriptors. At ungauged locations, adjustment factors are calculated either from nearby donor gauging stations (chosen using the approach outlined above) or set to 1, i.e. no adjustment, where no suitable donors could be found.

A record of the adjustment factor applied at each HEP is provided in Appendix F.

Figure 5-1: Adjustment factors for QMED at gauges and hydrological estimation points



5.5 Estimation of growth curves

Using the FSU approach, flood growth curves can be derived from analysis of annual maximum flows either at the site of interest (single-site analysis) or at a group of gauging stations chosen from a wide area (pooled analysis).

5.5.1 Sites suitable for single-site analysis

Single-site analysis uses annual maximum flows solely at the gauge of interest to estimate flood growth curves. It was carried out at all gauging stations included in the flood peak analysis (Appendix B).

Single-site estimates are typically avoided as they are vulnerable to the length and quality of peak flow data. Where the AMAX record length exceeds two times the return period, single-site estimates are deemed representative of the observed data. This record length is rarely achieved, particularly for higher return period estimates, therefore some weight can be given to single-site estimates if the record length is between one and two times the return period. Appendix B includes further consideration of the quality of the flood peak data, flood history and unusual catchment characteristics that may reduce confidence in pooled growth curves to ensure that the most representative growth factors were applied at each gauged location.

In UoM 29 single-site growth curves were deemed the most representative of the gauged catchment at Craughwell (29007) and Kilcolgan (29011). The single-site growth curves were applied at these gauges and nearby ungauged locations where appropriate. The application of growth curves to ungauged sites is discussed further in Section 5.5.6 below.

5.5.2 Selection of pooling groups

For pooled analysis, gauges are chosen on the basis of their similarity with the subject catchment according to three catchment descriptors; AREA, SAAR and BFIsoil. The report on FSU WP 2.2 presents two alternative equations for calculating the similarity of catchments according to these three descriptors. For the CFRAM, equal weight was given to each of these variables, applying the similarity distance formula given as Equation 10.2 in the report on FSU WP 2.2.

Not all gauges in Ireland were considered for use in pooling, because the analysis required to fit a flood growth curve makes use of the magnitude of each annual maximum flow, and thus it is necessary that even the highest flows are reliably measured. This excludes gauges where there is significant uncertainty in the high flow rating. The following gauges were considered as candidates for forming pooling groups:

- Gauges that were included in the Western CFRAM rating review process, where this led to a confident re-assessment of the rating, or to fitting of a new rating (13 gauges).
- Other gauges from the Western CFRAM area or elsewhere throughout the Republic of Ireland that are classed as A1 or A2 standard in the FSU dataset. This is the set of gauges that was used to develop the methods in FSU WP 2.2. OPW provided updated annual maximum series for their FSU gauges in March 2013 (91 of which are classed A1 or A2), containing data up to water year 2009-10. 28 additional gauges operated by EPA are classed as A1 or A2, and flood peak series for these have not been updated since the FSU research, so end in water year 2004-5.
- Gauges from Northern Ireland that are classed as suitable for pooling in the current version of the HiFlows-UK dataset (version 3.1.2, which contains data up to water year 2008-09) (37 more gauges).

The total number of gauges in the pooling dataset, allowing for some overlaps between the above categories, is 166.

The inclusion of gauges from Northern Ireland is beyond the work that was carried out for the FSU research. Adding these gauges increases the likelihood of finding similar catchments to form pooling groups, particularly for small catchments for which there is a shortage of gauged data in the Irish Republic. In this instance, the pooling group contents for the Craughwell and Kilcolgan catchments do not contain data from Northern Ireland. Whilst such data was assessed for inclusion in the pooling groups, it was discounted due to the combined assessment of all catchment characteristics, not solely the catchment area. The fact that some parts of the Western CFRAM area are adjacent to catchments in Northern Ireland adds weight to the argument for including data from the North. In addition, research (Molloy, 2011)[3] has shown that there is no observable difference between the forms of flood frequency distribution followed by the annual maximum flood datasets of Northern Ireland and the Republic of Ireland, and so it can be expected that data from Northern Ireland will be a useful addition to any pooled analysis. One assumption has been made to enable the inclusion of Northern Irish data; that the catchment descriptor BFIHOST (used in the UK) can be considered equivalent to BFIsoil. Although the two descriptors are calculated from different datasets, they are both intended to measure the same quantity, i.e. the baseflow index, which is a measure of the proportion of the annual flow hydrograph that derives from storage in the catchment.

FSU WP 2.2 recommends creating pooling groups that contain 5T years of data in total, where T is the return period of interest. As advised in WP 2.2, and to avoid possible contradictions between growth curves for different AEPs, a single pooling group has been chosen for each location, based on an AEP of 1% which has been defined as the principal AEP of interest. This equates to a return period of 100 years, and thus each pooling group contains just over 500 years of data.

No alterations were made to the pooling groups derived using the process described above as the gauging stations had already been screened according to the quality of their flood peak data. Although there is some evidence from research on UK data[4] that flood growth curves are affected by additional catchment descriptors such as FARL, the FSU research found that FARL was not a

[3] Molloy, James (2011). A Comparison of the Stochastic Flood Hydrology of the North and Republic of Ireland. Unpublished MSc thesis, NUI Galway.

[4] Kjeldsen, T.R., Jones, D.A. and Bayliss, A.C. (2008) Improving the FEH statistical procedures for flood frequency estimation. Science Report SC050050, Environment Agency.

useful variable for selection of pooling groups (uncertainty was greater when FARL was included than when it was excluded) and therefore no attempt was made to allow for the presence of lakes in the composition of pooling groups. Similarly, no allowance was made for arterial drainage in selecting pooling groups.

The membership of each pooling group created at the site of gauging stations is listed in Appendix B. Where suitable flood peak data are available at the gauge, it is listed as the top-ranking gauge in the pooling group. Most groups can be seen to contain gauges from a wide range of locations across Ireland, although there are few from the east coast, where the annual rainfall is low enough to exclude most gauged catchments from pooling groups created using characteristics of catchments in the Western RBD. There are few catchments from Northern Ireland in most groups; the exceptions being groups created for the smallest catchments. Most groups contain more gauges from the Western RBD than from other RBDs, thus focusing the analysis on catchments that are local as well as hydrologically similar.

5.5.3 Selection of statistical distribution

FSU WP 2.2 recommends considering two parameter distributions for single-site growth curves, either the extreme value type 1 (EV1, known as the Gumbel) or the 2-parameter log-normal distribution (LN2). Restricting the number of parameters to two helps reduce the standard error of the fitted distribution, albeit at a cost of a potential greater bias compared with 3-parameter distributions. In this assessment, both distributions have been fitted, and the goodness-of-fit assessed visually.

For pooled growth curves, WP 2.2 recommends considering 3-parameter distributions, because the extra data provided by the pooling group ensures that the standard error is lower than it would be for single-site analysis. The report states that either the generalised extreme value (GEV) or generalised logistic (GL) distributions are worth considering. In this assessment both have been fitted for each pooled analysis. In general, the GL distribution results in a growth curve that is more skewed, i.e. it may give similar or lower growth rates to the GEV for moderate probabilities, but it has a stronger upwards curvature which results in a steeper growth curve for low-probability floods. Molloy (2011) found that the GL distribution gave a better fit than the GEV for the vast majority of pooling groups in both the Republic and Northern Ireland. For the present study, the choice of recommended distribution has been made on the basis of visual inspection of plots comparing pooled growth curves with plotted flood peak data at gauging stations. In most cases, the GL distribution has been preferred as it appears more consistent with at-site flood peak data and is less likely to underestimate design flows for low probabilities.

5.5.4 Fitting growth curves

Both single-site and pooled flood growth curves have been fitted using the method of L-moments, as recommended in the FSU research. To calculate the pooled curve, the L-moments for each gauge in the pooling group have been weighted according to the record length of the gauge. This ensures that more weight is given to longer records, which provide more reliable estimates of the underlying flood frequency distribution.

5.5.5 Choice between single-site and pooled growth curves

Initially, both single-site and pooled growth curves were fitted at all 26 gauging stations on watercourses to be modelled for the Western CFRAM where there are at least five years of reliable flood peak data. The resulting growth curves for gauges in UOM 29 can be seen in Appendix B. The graphs show the annual maximum flows for each gauge and both the single-site and pooled growth curves. The horizontal axis shows return period rather than AEP because the software (WINFAP-FEH) does not provide the option to plot AEP.

At each gauge a preferred growth curve has been selected. There is a large amount of guidance available on the choice between single-site and pooled growth curves, including FSU WP 2.2, Gaume (2006)[5] and Environment Agency (2012)[6]. Factors that have been considered include:

[5] Gaume, E. (2006) On the asymptotic behaviour of flood peak distributions. Hydrol. Earth Syst. Sci, **10**, 233-243.

[6] Environment Agency (2012) Flood estimation guidelines. Operational instruction 197_08, issued June 2012.

- The length of the flood peak dataset at the gauge.
- The quality of the rating curve for measurement of high flows.
- The degree to which the catchment is unusual and therefore likely to be less well represented by other catchments in the pooling group.
- Information available from longer-term flood history, including quantitative data such as longer flow datasets at nearby gauges and more qualitative data from reports of earlier floods.
- The degree to which the curves fit the plotted flood peak data, bearing in mind the uncertainty of the plotting positions used to control where the data displays on the return period axis.
- The implied exceedance probabilities for the highest floods on record according to each distribution, and whether these are likely given what is known of the impact of the floods.

As an example of this last point, if the pooled growth curve is much less steep than the single-site curve, it might imply that the highest couple of floods recorded at the site both have annual probabilities lower than 1%. While this is theoretically possible it is highly unlikely, and a more likely explanation would be that the pooled growth curve underestimates the true growth curve for the catchment in question.

At the other extreme, a pooled curve that is much steeper than the single-site curve would imply high probabilities for the top few floods on record. It is possible to calculate the statistical likelihood of these probabilities being correct. For example, how likely is it that a 30-year long record contains no flood exceeding a 10% annual probability (10-year return period)? This question can be answered by calculating the probability of no exceedances in any 1 year (0.9) and then raising 0.9 to the power of 30 to calculate the probability of no exceedances in 30 years, which works out as 0.04, i.e. it is very unlikely that there will be no exceedances. To answer the question for a number of exceedances greater than zero, the binomial theorem can be applied.

Such calculations are considered in the discussions in Appendix B to help decide whether pooled growth curves are realistic in some cases where they differ markedly from the plotted flood peak data.

In some cases, the choice was straightforward as there was little difference between the single-site and pooled curves. This is the case at Clarinbridge. At Craughwell and Kilcolgan the single-site growth curves are considerable steeper than the pooled curves as a result of the November 2009 which is an outlier in the flood peak series. At both of these gauges the single-site curve has been preferred as the pooled curves imply unrealistically low probabilities for the 2009 flood.

5.5.6 Growth curves for ungauged sites

The standard FSU approach is to develop growth curves for ungauged sites using pooled analysis. This has been applied at the majority of sites, with an individual pooling group created for each site. Both GL and GEV growth curves have been fitted, for comparison. There is moderate variation in the pooled growth curves across the Western CFRAM study area:

- The 1% AEP growth factor from the GEV ranges from 1.56 to 2.52 with a mean of 1.96.
- The 1% AEP growth factor from the GL ranges from 1.63 to 2.60 with a mean of 2.04.

As is often the case, the GL gives slightly higher growth factors for low AEPs as it tends to have greater skewness than the GEV.

Given that the GL was judged to be the preferred growth curve at most gauging stations where pooled analysis was chosen, it was decided to adopt the GL for all ungauged locations too, apart from on watercourses with gauging stations where the GEV was chosen. As can be seen from the results in the above bullet points, the effect on the design flows if the GEV had been adopted would have been a reduction of the 1% AEP flow estimate by 4% on average.

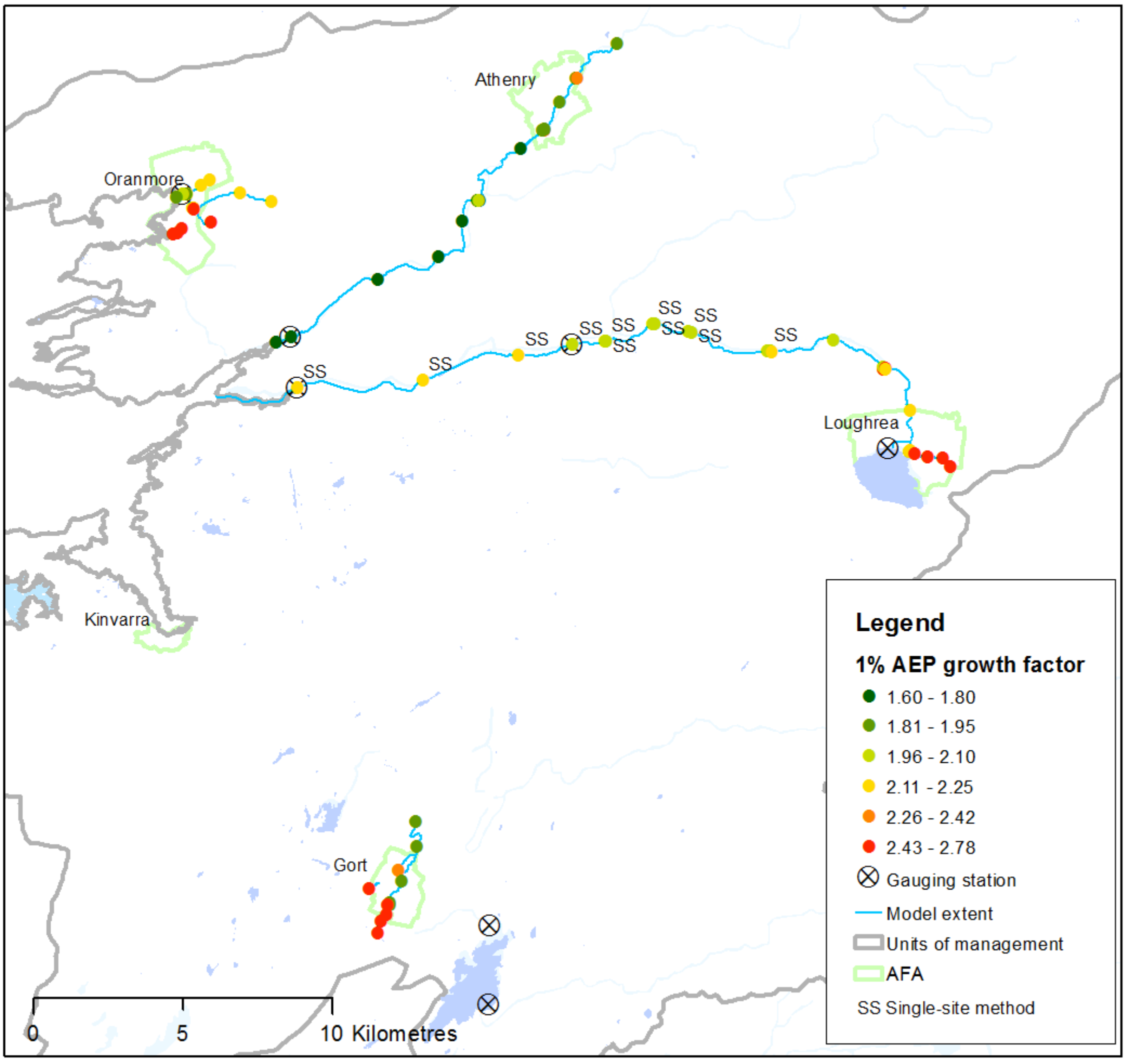
For sites on watercourses where there is a gauging station nearby at which the single-site curve is preferred, it is not appropriate to use a pooled growth curve as this may result in a sudden jump in the growth factor, leading to spatial inconsistency in the design flows. For this reason, single-site growth curves have been selected in such situations. Judgment has been used in deciding

how far away from each gauging station the single-site curve should be applied, before reverting to the pooled curve.

A record of the type of growth curve and the distribution applied at each HEP is provided in Appendix F.

Figure 5-2 shows the resulting growth factors for an AEP of 1%, i.e. the ratio of the 1% AEP flood to QMED. Growth factors show considerable variability between rivers, being lowest on the Clarinbridge, where the 2009 flood has less of an effect on the growth curves. The steepest growth curves are found on the smaller tributary catchments, with 1% AEP growth factors up to 2.8 on small watercourses in Loughrea, Gort and Oranmore.

Figure 5-2: Growth factors for the 1% AEP flood



5.5.7 Extension of growth curves to the 1000-year return period (0.1% AEP)

After reviewing the flood outlines produced by model runs which used the first iteration of design flows, some revisions to design flows were made in order to ensure flood levels and extents were not underestimated for the most extreme events. The initial flood outlines showed little out-of-bank flow in some areas, even for the 1000-year flood, which was considered unlikely to be realistic. The revisions included applying the FSR rainfall-runoff method to estimate the gradient of the upper portion of the growth curve for return periods in excess of 100 years.

The reasons for favouring the rainfall-runoff method over the FSU curve are that rainfall growth curves can generally be treated with more confidence than flood growth curves (owing to longer records, greater spatial consistency and fewer problems with data quality) and that adopting this method avoids the extremely low gradient growth curves that were derived at some HEPs using

the FSU methods. At some HEPs, the 1000-year flood was initially estimated to be as little as 13% greater than the 100-year flood. While there is no firm evidence on which to base estimates of floods as extreme as the 1000-year return period, this small growth rate was considered to be unrealistic. The corresponding percentages estimated from the FSR rainfall-runoff method did not fall below 44% (i.e. the 1000-year flood was at least 1.44 times greater than the 100-year flood).

In UK practice, it is also common to see occasional very low rates of growth from 100-year to 1000-year floods, and a widespread approach is to derive the upper part of the flood growth curve from an alternative method, usually the ReFH rainfall-runoff method. Environment Agency guidelines[7] advocate this approach, and selection of the 100-year return period as a pivot point is near-ubiquitous in the UK.

The extension of the growth curves was carried out by using the FSR rainfall-runoff method to estimate the ratios of the 200-year to 100-year and 1000-year to 100-year floods. These were then multiplied by the estimate of the 100-year flood given by the FSU methods described above. The FSR estimates were derived using FSR rather than FSU design rainfall since the FSU rainfall statistics are not intended for extrapolation up to the 1000-year return period.

It was not necessary to apply all aspects of the rainfall-runoff method to calculate the required ratios. The gradient of the flood growth curve depends on two principal factors: the gradient of the FSR rainfall growth curve and the way in which the percentage runoff increases with rainfall magnitude as a result of the DPRrain term in the FSR calculation of percentage runoff. A simplified calculation was carried out, with a single value of the FSR rainfall parameters M5-2 day and Jenkinson's r applied to all catchments within a given UoM. The main variations in the gradient of the growth curve were due to the soil type, which was evaluated individually for each HEP from a digitised version of the FSR soils (WRAP) map.

A consequence of this adjustment is that the upper portion of the final CFRAM growth curves is steeper in areas with low SPR, i.e. more permeable soils. This is in accordance with expectations that permeable catchments, including karst areas, may occasionally experience particularly extreme floods during events which cause the catchment processes to switch to those associated with more impermeable catchments, perhaps due to filling of upstream storage in turloughs, caves and other karst features.

5.6 Final design flows from FSU method

Design flows for each AEP and at each HEP have been calculated by multiplying the estimates of QMED by the appropriate growth factor, and by application of FSR rainfall-runoff ratios for 0.2% and 0.1% AEP events. The flows are supplied in Appendix F and also digitally in the form of a shapefile and a spreadsheet.

A summary of the methods used for estimating the design flows for each AFA in UoM 29 can be found in Chapter 7.

The final design flows have been used as inflows to the hydraulic models, in a process which is described in the relevant AFA Hydraulic Modelling Report.

5.7 Application of FSR rainfall-runoff method for Loughrea

Design flows for the watercourse flowing out of Lough Rea have been estimated using flood routing to represent the substantial effect that the lough has on flood flows.

Inflows to the lough were estimated using the FSR rainfall-runoff method, applied at the HEP labelled SCLS_001, which is just downstream of the main outlet. Most catchment descriptors for this location were taken from FSU node 29_660_001 which includes the whole area draining to Lough Rea, and then modified as described below.

The surface area of the lake forms a significant proportion of the catchment draining through the lake outlet so an allowance has been made for rain falling on the water surface (which is not subject

[7] Environment Agency (2012) Flood Estimation Guidelines.

to any losses). The surface area of the lake is 3.0km^2 and the area of the combined catchments draining into the lake is 9.0km^2.

To be more representative of the streams flowing into the lake, the slope and length characteristics (S1085 and MSL) were calculated not at the outlet of the lake but at the main inlet to the lake (FSU node 29_640_4) to exclude the portion of the watercourses covered by the lake.

Table 5-1 lists the characteristics used to set up the rainfall-runoff model.

Table 5-1 Catchment characteristics used for the FSR rainfall-runoff model at Loughrea

Catchment characteristic	Value	Source
AREA	9.0 km^2	FSU and OS (= 11.97km^2 minus lake area of 3.0km^2)
MSL	2.58 km	FSU descriptors for main inflow to lake
S1085	14.1 m/km	FSU descriptors for main inflow to lake
URBAN	0.12	FSU (= 2 x URBEXT/100)
SAAR	1134 mm	FSU
r	0.30	FSR map
M5-2day	57 mm	FSR map
SPR	18%	FSR WRAP map: 7km^2 (0.78) of class 1 and 2km^2 (0.22) of class 4 SPR = 10S1 + 47S4 = 10x0.78 + 47x0.22 = 18%.

A design storm was specified using design rainfall from the FSR. The initial storm duration was set to 6.25 hours, which would be the critical duration in the absence of any reservoir lag. This will be amended during the hydraulic modelling to allow for the lag effect introduced by the lough. The design flows for Lough Rea will be finalised during the hydraulic modelling.

Initial results from this approach did not give a great enough increase in lake level, with the November 2009 lake levels not being replicated even in the 0.1% AEP model. The QMED inflows were then calibrated to achieve a LMED lake level based on the lake level gauge 29070. The scaling required to achieve this was then transferred up to the larger return period events to produce outputs more in line with observed lake levels.

For full details of the development of the Loughrea model please see the Loughrea AFA Hydraulic Modelling Report.

5.8 Checks on the design flows

5.8.1 Calibration, validation and checking

The brief for CFRAM studies requires the consultant to "calibrate and validate the estimates of the design flood parameters … to recorded data as far as reasonably possible, based on historic or recorded flood event data."

The design flows have been derived by direct analysis of flood data, as far as its availability and quality permit, so they will naturally be consistent with that data. Flood data has been used to estimate QMED at gauges, to adjust QMED at ungauged sites, to fit growth curves, to decide between single-site and pooled growth curves, to estimate time to peak for the rainfall-runoff method and to derive average hydrograph shapes.

However, it cannot be claimed that the design flows have been calibrated or validated because, while measurements of river level and flow are feasible, there is no way of measuring the probability of floods. Thus there is no meaningful way of calibrating design flows against observations, unlike say calibration of a hydrological or hydraulic model in which model results can be compared against modelled flows or levels. Any so-called calibration of design flows would give a spurious impression of confidence in what are statistical estimates. Validation of resulting flood extents for various return periods has been undertaken as part of the hydraulic modelling work.

In addition, design flows have been checked using a number of tests intended to identify any results that fall outside expected ranges or are inconsistent with other results. The tests have included:

- Checks that growth factors are within expected ranges. The range of 1% AEP growth factors from the pooled analysis is 1.63 to 2.78. None of these values are unexpectedly high or low. This range can be compared with the equivalent factor taken from the FSR regional growth curve for Ireland: the factor for the 1% AEP divided by that for the 50% AEP gives a ratio of 2.06. Some of the single-site growth curves that are preferred over pooled curves have more extreme growth factors, as discussed in Appendix B.
- Checks on the AEPs for observed events that are implied by the derived flood frequency curves at gauging stations. The findings are described in Appendix B.
- Checks for spatial consistency between design flows at different locations. These are described below.

5.8.2 Checks for spatial consistency

Spatial consistency, or coherence, is an expected characteristic of design flow estimates throughout a catchment, reflecting the behaviour of the physical system. Estimates should vary gradually along the length of a watercourse unless there are features that reduce or increase the rate at which water is routed through the catchment, potentially causing a step change in flow.

Design flows can be deemed spatially consistent if they gradually increase downstream, with step changes only at confluences or decreases in the downstream direction where a physical cause can be attributed. It is therefore expected that peak flow estimates downstream of a confluence should be consistent with those of the tributary inflows, with:

Highest tributary flow estimate < Downstream flow estimate < Sum of peaks on tributaries

Given the variability in catchment characteristics, and thus the timing and magnitude of peak flows, no fixed relationship can be given between the downstream flow estimate and those of the tributaries. It is therefore necessary to examine the modelled watercourses in turn to ensure that flows are consistent between confluences and that the above condition is met at confluences. If it is not, reasons should be determined for the inconsistency which can be taken into account during the modelling process.

Following the methodology outlined above for estimating the design flows, there is a fine balance between applying various methods between HEPs to account for local data and ensuring consistency between HEPs where different methods have been used. Various approaches have been incorporated into the study, such as applying weighted adjustment factors for QMED, using pooling groups and checking catchment descriptors to derive the most robust estimates throughout the catchment. Incoherence is possible where the chosen method changes between HEPs. Checks of both the physical causes for apparent incoherence and step changes as a result of the methodology are therefore particularly important to verify that realistic flow estimates are incorporated into the hydraulic models and so detailed consideration of inconsistencies is discussed in each of the relevant hydraulic modelling reports.

The approaches in Section 5.4 describe the use of donor gauging stations, adjustment factors, weighted factors and catchment descriptors to estimate QMED. As these methods have been applied to various reaches, it is possible that changes in the adjustment factor for QMED, growth factors (in the case of HEPs where a pooled approach has been used) and direct estimates of QMED from catchment descriptors, may not be spatially coherent. Step changes in the flows were related back to each of these calculation stages where necessary.

Checks were made of the following at both the 50% and 1% AEP for AFAs and HEPs on all modelled watercourses:

- Consistency in flow estimates downstream
- Consistency at confluences
- Consistency with gauged data (where available)
- Consistency in flows between return periods.

Where spatial incoherence was apparent, catchment descriptors were reviewed for physical reasons for the flow estimate. Apparent spatial inconsistencies were found in some instances, typically for HEPs with small areas derived solely from catchment descriptors. These have been reviewed and can be explained by changes in the physical catchment downstream or large

differences in catchment parameters between tributaries. The key observations and their potential causes have been summarised in Table 5-2 below.

Table 5-2 Reasons for apparent spatial inconsistencies

Observation	Potential Cause
Downstream flow estimate is less than the greater of the two tributaries	Occurs where the change in Area is outweighed by more extreme changes in other catchment descriptors. For example, where the influence of a lake, floodplain characteristics or extreme differences in rainfall characteristics on an incoming tributary affects downstream catchment descriptors such that there is a reduction in QMED, a change in pooling group members or both.
Downstream flow estimate is greater than the sum of the two tributaries	FSU QMED equation exacerbating extreme catchment descriptors downstream of confluence – typically where tributary catchments are considerably different in character (particularly BFIsoils/FARL)
Decrease in flow downstream – mid reach	Floodwaters spreading out into the floodplain or loughs between HEPs. Impermeable headwaters from soil characteristics or urban extent resulting in flow attenuation downstream. Increased runoff rates to the upstream HEPs due to impermeable soils may exacerbate flows. If the catchment becomes more permeable downstream, the increased area may not outweigh the increased infiltration and flows may decrease in a downstream direction.

Some of these apparent inconsistencies can be explained by a physical cause and therefore should be represented within the hydraulic model. It is also possible, particularly when QMED is estimated solely from catchment descriptors, that the influence of these physical changes is exacerbated by the FSU equation. In these cases, the HEPs should be used to derive the general flow patterns downstream which should be replicated by the model, but the peak flows derived for each HEP may not be matched exactly. In areas where the flood risk is high (for example, due to the presence of properties) it is recommended that flows are adopted that represent a conservative estimate of risk by applying the larger of the HEP design flows at the downstream location.

Inconsistencies in design flows may also arise from changes in method used within a catchment. Particular attention has been paid throughout the design estimate calculation to checking the consistency of the following:

- Adjustment factor for QMED downstream and at confluences
- Changes in pooling group and growth factors
- Consistency between HEPs where the method of using pooled or single site analysis changes.

The following examples describe the locations where these inconsistencies are most likely to occur:

Table 5-3 Inconsistency locations

Cause
QMED adjustment factor differs significantly between upstream and downstream of a confluence – typically a result of changing catchment descriptors at the confluence
QMED adjustment factor is particularly large and no weighted adjustment is applied
Change in pooling group downstream reducing growth factors at a HEP (e.g. GOR_004 to CNW_001)
Inconsistency in QMED estimate as a result of change between pooled and single-site growth curves

Where the applied methodology appears to derive inconsistent flow estimates at HEPs, checks have been undertaken to ensure the calculations are correct. Consistent results are produced by each individual method however inconsistencies may arise where the method changes along a

watercourse. The choice of methodology has followed a detailed examination of the flow characteristics for each reach and therefore in cases where such inconsistencies arise the flow estimates should be interpreted during the modelling stage as follows:

- If the HEP is located upstream, in the vicinity of an urban area, flows should be used which represent a conservative estimate of flood risk. For example, the greater of the tributary inflows should be applied downstream of the confluence in the case of a decrease in the flow downstream.
- If the HEPs upstream of a confluence represent two catchments of significantly different catchment characteristics, the tributary inflows should be treated with more confidence than the downstream flow estimate.
- Where step changes occur as a result of a change in methodology, the greater of the estimates should be applied. A weighted approach to the derivation of growth factors has been applied along certain reaches to minimise such step changes.

The final design flows derived for the HEPs reflect both the physical catchment and the methodology used to extrapolate QMED to estimate events of larger magnitude. There are a few instances where, due to the reasons listed above, design flows are not spatially consistent. Consideration will be given during the modelling process to these locations, matching the derived values where possible, but allowing for deviations where modelling judgment chooses to favour particular HEP estimates. This may include, but is not exclusive to the three examples listed above. Further details regarding these decisions will be included in the reporting of the modelling methodology.

6 Estimation of hydrograph shapes

6.1 Overview of approach to hydrograph generation

For the vast majority of rivers in the Western CFRAM, design flows have been derived using the FSU methods to estimate peak flows by statistical analysis. At locations where inflows to hydraulic models are needed, it is necessary to provide a hydrograph shape for use in combination with the estimated peak flows.

When setting inflows to hydraulic models it is important to create a set of inflows from the various tributaries that are consistent in terms of their magnitude, timing and duration, so that the hydrographs combine in a realistic way at confluences.

The FSU includes a set of methods (published in FSU WP 3.1) for creating normalised hydrograph shapes (referred to as *characteristic flood hydrographs*) on gauged and ungauged catchments. For gauged catchments, characteristic flood hydrographs can be created by averaging the widths of observed hydrographs, referred to as a Hydrograph Width Analysis (HWA). For ungauged catchments, the FSU method allows characteristic flood hydrographs to be produced using a mathematical function whose parameters can be estimated from catchment descriptors. These methods are intended for use at individual locations and do not provide any information on the relative timings of hydrographs at confluences. A technique for estimating the relative timings of inflows was developed in FSU WP 3.4, in which the time difference between the two peaks is estimated from a regression model using differences in the descriptors of the two confluent catchments.

An alternative approach to creating hydrograph shapes is the older Flood Studies Report (FSR) rainfall-runoff method, in which design flood hydrographs are created from a design rain storm in conjunction with a unit hydrograph whose time to peak can be estimated either from local hydrometric data or from catchment characteristics. The hydrograph can be scaled to match a preferred peak flow, for example estimated using FSU methods. An advantage of the FSR method is that all hydrographs for the various inflows to a model can be created from the same design rain storm, thus imposing a realistic structure in terms of duration and timing of the inflows.

Both the FSU and FSR methods have been tested, as discussed in the following sections. The results have been compared at selected sites in order to select a preferred approach. For some of the largest rivers, a frequency analysis of flood volumes was carried out. The results have been used as a check on the volumes calculated from the hydrograph shapes when combined with the design peak flows.

The tests described in the sections below cover sites throughout the Western RBD as their aim was to provide information to assist the choice between alternative methods. The methods that were selected for individual AFAs in UoM 29 are summarised in Chapter 7.

6.2 Implementation of FSU hydrograph method

At gauging stations that are near either AFAs or upstream limits of hydraulic model reaches, characteristic flood hydrographs were created by taking the median widths of large numbers of normalised observed hydrographs. A characteristic hydrograph shape was created by fitting a combination of a gamma function and an exponential curve, the latter defining the recession portion of the hydrograph, to the median hydrograph widths. The analysis was carried out using the HWA software developed in FSU WP 3.1, and the results are given in Appendix D. The appendix includes results for all gauging stations that were analysed in the Western RBD, since the choice of method for application within each UoM has been based on examination of all the results.

At ungauged flow estimation points, characteristic flood hydrographs were derived using a combination of a gamma function and an exponential curve, as for the hydrograph width analysis. The report on FSU WP 3.1 presents a set of regression equations that allow the three parameters of these functions to be estimated from the following catchment descriptors:

- BFIsoil – the baseflow index estimated from soil characteristics

- FARL – a measure of flood attenuation due to reservoirs and lakes
- ALLUV – the proportion of the catchment covered in alluvial deposits
- ARTDRAIN – the proportion of the catchment that benefits from arterial drainage schemes
- S1085 – the slope of the main channel

An alternative method from WP 3.1, using a parabolic function whose parameters are the width of the hydrograph at 50% and 75% of the peak flow, was not applied as it defines only the top half of the flood hydrograph. The report on WP 3.1 emphasises that care should be taken in applying the methods for ungauged catchments, and that the resulting hydrographs should be verified against observations if at all possible.

The regression equations for predicting the parameters of the hydrograph functions have been criticised (for example in FSU WP 3.4) for not including any term that represents catchment size. One potential way round this limitation may be to adjust the parameters by transferring information from a representative gauged catchment, termed a *pivotal station* by OPW. This approach is not discussed in the report on FSU WP 3.1. One way to implement it would be to identify a nearby gauged catchment that is physically similar to the catchment of interest (in particular in terms of area or stream network length) and then calculate an adjustment factor for each hydrograph shape parameter similarly to the way in which pivotal stations are used for adjusting QMED, i.e. the initial estimate of the parameter, from the descriptors of the subject site, is adjusted using the ratio of gauged and catchment-descriptor estimates of the parameter calculated at the pivotal station.

OPW have developed a spreadsheet called Hydrograph Shape Generator (version 3) that is based on the FSU method but it implements the transfer from a pivotal station quite differently to the way discussed above. The spreadsheet is intended for internal OPW testing, interpretation and training and is subject to ongoing development and correction. It allows the user to select a pivotal station, stressing that selection of pivotal stations should be based on the user's knowledge of the area. Where local knowledge is not available, the spreadsheet selects a pivotal station on the basis of three descriptors: S1085, BFIsoil and FARL (the text in the spreadsheet says that AREA is used but the calculations in fact use S1085 instead). The spreadsheet then copies the gauged hydrograph shape parameters (which have been derived from hydrograph width analysis) directly from the pivotal station to the subject site, with an urban adjustment. It does not make any use of the regression equations produced in WP 3.1. It should be noted that the method of transferring parameters between catchments does not appear to be based on published research. Furthermore the spreadsheet, if applied without local knowledge, does not make any allowance for catchment size when determining hydrograph shape.

This spreadsheet has been used for comparison with the results of the WP 3.1 procedure, (not including any adjustments to the procedure to allow for catchment size) for ungauged catchments at a number of example sites in the Western CFRAM. Pivotal sites have been selected manually, taking into account similarity and proximity of catchments. Catchment descriptors used in the derivation of the hydrograph shape parameters were checked for similarity to the subject site, in addition to other characteristics which may influence the hydrograph shape, such as AREA, URBEXT, DRAIND and MSL. Local, hydrologically similar stations were preferred over those situated further away. In some cases, more than one pivotal site was selected to test the effect on the resulting hydrograph.

6.3 Implementation of FSR rainfall-runoff method

In the rainfall-runoff method, the shape and duration of design flood hydrographs depend on two factors: the time to peak of the unit hydrograph, Tp(0), and the duration of the design storm. The recommended storm duration, D, depends on Tp(0) and the annual average rainfall (SAAR), although in practice for catchment-wide modelling it is appropriate to use a common value of D for all subcatchments, in which case D may be derived by trial and error, aiming to find the critical duration for the main site(s) of interest within the model. The concept of critical duration is less relevant when the method is being applied only to determine the shape of flood hydrographs, which are to be scaled to match preferred peak flows, as is the case in the WCFRAM study.

The main influence on the duration of the design hydrograph is thus the value of Tp(0). This can be estimated directly from rainfall and river level data (which has not been carried out for UoM 29 given the absence of Met Éireann recording raingauges), or indirectly from catchment

characteristics. A regression equation in Flood Studies Supplementary Report 16 (FSSR16) uses the following characteristics to predict Tp(0):

- S1085 – the slope of the main channel
- URBAN – the fraction of the catchment classed as urban on OS mapping
- SAAR – the average annual rainfall
- MSL – the length of the main stream channel

All of these except URBAN are also FSU catchment descriptors. URBAN can be estimated from the FSU descriptor URBEXT using the approximation given in the report on FSU WP3.4:

URBAN = 1.567 URBEXT

The inclusion of MSL means that the duration of the resulting hydrograph will vary with the size of the catchment, unlike in the FSU method for ungauged catchments.

6.4 Comparisons of alternative methods for hydrograph shape generation

6.4.1 General approach

Since the Western CFRAM covers a large number of watercourses, it is desirable to select a method for production of hydrograph shapes that is suitable for as many watercourses as possible, to avoid having to apply multiple methods as far as possible. The primary requirement is for a method that results in a realistic duration and volume of flood water for the design flood that will be used to run the hydraulic models. These aspects of the flood will affect the impact on land and properties and the assessment of schemes for flood management. It is also important that the chosen method is capable of producing consistent hydrographs for input to models with multiple tributaries, as discussed above.

6.4.2 Summary of inception stage comparisons

The methods discussed above have been compared at two sets of example catchments. First, in the inception stage, hydrograph shapes were calculated directly from observed data using hydrograph width analysis at 21 gauging stations. The results were compared with hydrographs produced using the FSR rainfall-runoff method solely from catchment descriptors (Appendix D). This gives an indication of whether the rainfall-runoff method is capable of producing realistic hydrograph shapes at gauged sites, and therefore if results are likely to be applicable to ungauged sites.

For both stations analysed within UoM29 (Rathgorgin and Craughwell), the FSR method produced a flood hydrograph that is much narrower than that derived from observed events. Unsurprisingly, the unusual nature of these karst catchments is not well accounted for in the FSR method. Whilst it may initially appear that these gauges would provide useful information on the response of karst catchments, in reality the only AFA where this would be of benefit is Loughrea. In this instance the presence of Lough Rea means that the catchments at Rathgorgin and Craughwell are too dissimilar to the AFA site to be of use and indeed, a site specific approach has been adopted to develop the hydrology at this site, Section 5.7. The method for deriving hydrograph shapes at AFAs has therefore not incorporated data from observed floods at these stations.

6.4.3 Additional tests for main stage

A second set of tests has been carried out for the main stage hydrology, at a set of five gauged and five ungauged catchments chosen to be representative of the typical range of catchment locations and sizes found across the Western RBD. The catchments are listed in Table 6-1. For these catchments, the following methods have been applied for calculation of hydrograph shapes:

- FSU with hydrograph shape parameters calculated from catchment descriptors using the regression formulae from WP 3.1 (“FSU ungauged” method).
- FSU transferring the hydrograph shape parameters from one or more pivotal sites, selected using judgement, with the transfer carried out using the spreadsheet from OPW (“FSU pivotal” method).

- FSR rainfall-runoff using catchment descriptors to estimate Tp(0) ("FSR" method).

For the five gauged catchments, hydrograph shapes from the above methods have been compared with those constructed directly from the observed data (taken from the inception phase analysis). For the five ungauged catchments, the shapes have been assessed in the light of the order of magnitude of hydrograph duration that would normally be expected for a catchment of that type.

In addition, a more objective assessment of the hydrographs has been carried out by multiplying the dimensionless hydrographs by the design peak flow and then assessing the resulting design flood hydrograph using the IBIDEM technique. IBIDEM stands for Interactive Bridge Invoking the Design Event Method and was developed within FSU WP 3.5. It involves assessing a design hydrograph produced using FSU (or other) methods in the light of the FSR rainfall-runoff model structure. IBIDEM is a web-based software package that calculates the time to peak and standard percentage runoff parameters that would be necessary for the FSR rainfall-runoff model to produce an output similar to the FSU design hydrograph. If the resulting parameters have unrealistic values it is an indication that the input hydrograph may not be appropriate given the nature of the catchment.

IBIDEM requires inputs including selected FSU catchment descriptors and a table of design rainfall depths for the catchment. The latter has been generated for each example catchment using the FSU design rainfall statistics (WP 1.2). For medium and large catchments, the design rainfalls have been calculated from spatially averaged parameters of the rainfall depth-duration-frequency model. This is the approach recommended in Met Éireann Technical Note 61. For small catchments, parameters have been chosen at a single grid square within the catchment.

6.4.4 Results of visual comparison of shapes

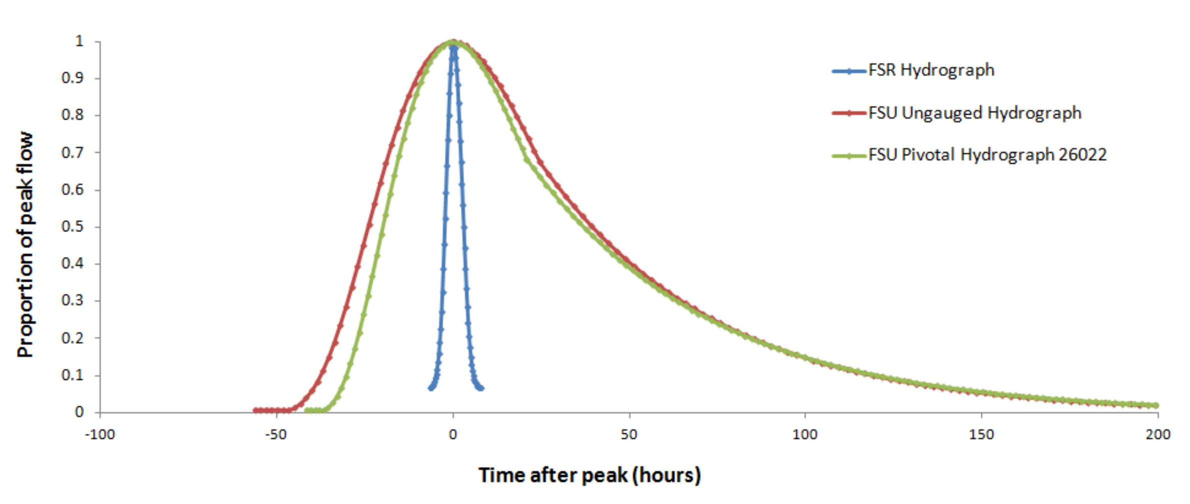
The visual comparison of shapes has been completed to confirm preferred choice of method at ungauged sites; the analysis has been completed at gauged sites so that each method can be compared against observed data. The results of the hydrograph shapes comparison are presented in Appendix E in the form of a summary sheet for each of the ten example catchments across the Western RBD showing the hydrographs and listing the parameters used to produce them and the pivotal sites that were chosen. Catchment descriptors for these and all gauges discussed in the following section are provided in the digital deliverables, Section 12.

Out of the five gauged catchments, the FSU ungauged method appears to give the best fit to observed hydrographs at two gauges, and the FSU pivotal method (implemented using the OPW spreadsheet) at another two gauges. At all four of these gauges, the FSR method gives a fit that is judged to be acceptable. At the fifth gauge, on the Castlebar River at Turlough, none of the methods tried gives a hydrograph that matches the observed events; the comparison of the methods for this gauge is shown in Appendix E.

For the five ungauged catchments, the results of the various methods were highly variable. The FSR hydrograph was similar to those from the FSU methods at one site (Grange at Corrofin) but produced a narrower (i.e. shorter-duration) hydrograph elsewhere. The FSU pivotal method produced a narrower hydrograph than the FSU ungauged method at four of the five sites, although the difference was minor in two of these cases.

The difference between FSU and FSR hydrographs was particularly marked for one of the example catchments, the Carrigans Upper watercourse at Ballymote in UoM 35 (Figure 6-1). At half the peak flow, the FSU hydrographs have a duration of 64 and 56 hours (ungauged and pivotal respectively) whereas the FSR hydrograph lasts for 5.25 hours. To put this into context, it is helpful to know that the catchment in question has an area of 2.5km^2. In the absence of backwater effects (which are not represented by any of the methods applied), it would not generally be considered realistic for such a small catchment to give rise to floods that last for days.

Figure 6-1: Comparisons of hydrograph shapes for the Carrigans Upper watercourse at Ballymote



6.4.5 Results of comparisons using IBIDEM

The parameters fitted by IBIDEM for the ten test catchments are shown in Table 6-1 below.

Table 6-1: Results of IBIDEM tests to assess hydrographs at ten example catchments

(a) Example gauged sites

	30020 Dalgan at Ballyhaunis	32011 Bunowen at Louisburgh	34018 Castlebar at Turlough	35002 Owenboy at Billa Bridge	35073 Dalgan at Sligo
FSR hydrograph shape					
Time to Peak (hr)	7.0	4.7	5.8	5.2	9.7
Standard Percentage Runoff	8.6	91.4	**-1.7**	23.4	11.0
FSU hydrograph shape from catchment descriptors					
Time to Peak (hr)	15.2	Run failed	95.9	13.7	66.2
Standard Percentage Runoff	20.7	**>100**	32.7	53.5	51.0
FSU pivotal hydrograph shape (first donor)					
Time to Peak (hr)	45.5	3.1	66.4	97.0	9.2
Standard Percentage Runoff	59.7	70.3	25.4	**245**	10.5
FSU pivotal hydrograph shape (second donor)					
Time to Peak (hr)	6.8	n/a	62.2	9.6	n/a
Standard Percentage Runoff	8.5		24.2	37.9	
Median observed shape from HWA					
Time to Peak (hr)	10.7	3.7	99.2	7.2	68.5
Standard Percentage Runoff	13.2	79.0	33.5	30.2	52.1

(b) Example ungauged sites

	Athenry at Athenry	Carrigans Upper at Ballymote	Grange at Corrofin	Loughrea	Swinford at Swinford
Peak flow for 1% AEP from FSU (m^3/s)	8.1	4.6	40.2	6.1	8.2
FSR hydrograph shape					
Time to Peak (hr)	7.6	3.3	12.9	3.8	5.3
Standard Percentage Runoff	9.1	48.2	15.0	11.9	15.8
Storm Duration (hr)	17	7.25	27	8.25	13
FSU hydrograph shape from catchment descriptors					
Time to Peak (hr)	29.4	36.4	17.4	Run failed	14.3
Standard Percentage Runoff	30.0	**341**	21.2	**>100**	38.0
Storm Duration (hr)	63	79	37		33
FSU pivotal hydrograph shape					
Time to Peak (hr)	36.4	30.5	19.7	Run failed	11.9
Standard Percentage Runoff	35.3	**297**	24.0	**>100**	31.3
Storm Duration (hr)	77	67	41		27

Both the time to peak (Tp(0)) and standard percentage runoff (SPR) parameters fitted by IBIDEM provide useful information. However, they must be interpreted with care as IBIDEM is a rather complicated concept that, applied here, combines elements of several different methods.

For Ballymote, Loughrea, Louisburgh and Billa Bridge the IBIDEM runs using the FSU hydrograph shapes (from catchment descriptors, pivotal sites or both) resulted in inferred SPR values greater than 100%, i.e. physically impossible. There are three possible explanations for the very high SPR values:

1. The FSU hydrographs are too prolonged;
2. The supplied peak flow from FSU is too high for the catchment;
3. The FSR rainfall-runoff method, applied using FSU design rainfalls, is underestimating design floods for the catchment (hence it appears FSU design flows are over-estimated in comparison).

The first explanation seems very likely given the extremely long durations of some of the FSU hydrographs. This is a useful finding which helps to confirm that the FSU method of generating hydrograph shapes (whether applied using catchment descriptors or via OPW's pivotal spreadsheet) does not always yield hydrographs that are consistent with the properties of the catchment.

Elsewhere, in nearly all cases IBIDEM yields longer Tp(0) parameters when fitting to the FSU hydrograph shapes than to the FSR hydrographs. The consequence is higher fitted SPR parameters for the FSU hydrographs; this is because when the flood runoff is spread out over a longer time, it is necessary to produce a greater relative volume of runoff in order to match a given peak flow. Implied SPR parameters fall in the following ranges (ignoring results below 0% or above 100%):

- FSR hydrographs: 11% to 91%, mean 23%
- FSU hydrographs from catchment descriptors: 21% to 53%, mean 35%
- FSU hydrographs from pivotal site: 10% to 70%, mean 37%
- Median observed hydrographs from HWA: 13% to 79%, mean 42%

To put these values into context it may help to know that SPR when estimated from the FSR soil maps (WRAP maps) ranges from approximately 10% at Athenry and Loughrea up to 28% for the Grange at Corrofin and at Ballyhaunis, 37% for Ballymote, Swinford and Turlough and 50% for Louisburgh, Billa Bridge and Sligo. At Athenry, Loughrea and Ballymote the implied SPR parameter from the FSR hydrograph gives a reasonably close match to that estimated from soil

characteristics. At Corrofin, Swinford, Turlough and Sligo the FSU hydrographs give a closer implied SPR to that estimated from soils. Elsewhere the picture is more varied. These results should not be taken to mean that hydrograph shapes are necessarily any better if they give a closer match to SPR values from the WRAP maps; there are various possible reasons for the discrepancies, as discussed below.

When IBIDEM is applied to a design flood hydrograph whose shape has been generated from the FSR rainfall-runoff method, the fitting process in IBIDEM will inevitably yield a hydrograph with a very close fit, whose Tp(0) parameter is more or less identical to the time to peak of the unit hydrograph that was used to generate the initial hydrograph shape. On gauged catchments the fitted Tp(0) from the FSR method can be compared with that fitted to the median observed hydrograph shapes. This replicates the visual comparison of hydrograph shapes carried out in the inception stage. For three of the five catchments there is a reasonably close match. The exceptions are Sligo, where Lough Gill results in major attenuation that is not accounted for in the FSR method, and Turlough. For the Castlebar at Turlough the FSR hydrograph has a Tp(0) very much shorter than that fitted to the observed hydrographs. This large discrepancy is also manifested in the implied SPR which is negative for the FSR hydrograph. There are three possible explanations for this and for some of the other fitted SPR values from FSR hydrographs that appear to be on the low side (such as Ballymote and Ballyhaunis):

1. The FSR hydrograph shape is too narrow for the supplied peak flow, hence the volume of runoff is too low;
2. The supplied peak flow from FSU is too low for the catchment;
3. The FSR rainfall-runoff method, applied using FSU design rainfalls, is underestimating design peak flows for the catchment (hence it appears FSU design flows are overestimated in comparison).

Explanation number 3 is a likely candidate in some cases, given the widespread tendency for the FSR rainfall-runoff method to result in design flows that exceed those obtained from direct analysis of flood peak data.

6.5 Overview of selected approach for hydrograph shapes

For most hydraulic models, it is recommended that hydrograph shapes are produced using the FSR rainfall runoff method. The principal reasons for this decision are:

- The FSU hydrograph shape method for ungauged catchments, whether applied using catchment descriptors or the pivotal catchment approach implemented in OPW's spreadsheet, does not take into account the size of the catchment and so can produce hydrographs that appear unrealistic.
- At four of the ten test catchments for which IBIDEM was applied, the FSU method resulted in inferred SPR values greater than 100%.
- At many of the 21 gauging stations for which median hydrograph shapes have been created, the FSR method gives an acceptable match to the observed hydrograph, even without any adjustment of the time to peak using local data (Section 6.4.2).
- The FSR method, applied using a uniform design storm for all sub-catchments within a model, imposes a structure on the model inflows with realistic relative timings of the hydrographs. This avoids the need to apply the FSU regression model for relative timings of hydrographs at a confluence, which is associated with a large standard error.

The duration of the FSR hydrograph is affected by the duration of the design storm as well as the time to peak of the unit hydrograph. As mentioned above, a uniform design storm duration will be applied to each sub-catchment within a model. Because the FSR method is being used only to control the shape of the hydrographs rather than to provide an accurate representation of the catchment response and therefore magnitude of the peak flows, it is not appropriate to use this method there is no need to identify a critical storm duration, i.e. one that results in the highest peak flow or water level. However, in order to ensure a realistic flood duration, the duration of the design storm has been related to the time to peak for the principal watercourse in the model, using the FSR formula that evaluates storm duration from time to peak and SAAR. This approach has the potential to overestimate flood risk on smaller tributaries where the storm duration has been developed with the larger watercourse in mind. The resulting flood risk on these tributaries will be

reviewed within the hydraulic modelling phase and, if necessary, additional runs with the storm duration more suitable to the size of the tributary will be completed. The sensitivity of the flood risk extents to the assumption that the critical storm duration can be derived from catchment descriptors, where no other information is available, will be investigated as part of the hydraulic modelling work.

However, within UoM 29 there are a number of unusual features that require a modification to this approach and the use of observed data rather than catchment descriptors to derive appropriate storm durations.

At Gort the FSR hydrograph shape has been heavily lengthened to better represent the observed hydrograph from the 2009 flooding. At Loughrea, the above approach has been modified by using the FSR method to derive the inflow to a routing model of the lough as explained in Section 5.7. For the Loughrea MPW downstream of the Craughwell gauge, inflows have been developed using the gauge data rather than FSR alone. In fact within UoM 29 it is only Athenry where a standard FSR approach has been applied. Full details of the methods applied to develop the hydrograph shapes for the Gort and Loughrea AFAs are provided in the relevant hydraulic modelling report.

7 Summary of flood estimation process

7.1 Summary of steps leading to design flood hydrographs

The chapters above have described a detailed investigation of alternative methods and provided a justification for the chosen approach. A summary of the process that has been followed to implement this approach is given in Table 7-1. It shows how there are some differences in the ways that gauged and ungauged locations have been treated. The table is a deliberately simplified summary and there will be some locations where the methods applied are slightly different from those outlined in the table. The following section outlines the approach used for each individual AFA.

Table 7-1: Summary of flood estimation process

Step	HEP with flow data	Ungauged HEP with suitable donor site	Ungauged HEP with no donor site
1	Obtain catchment descriptors from FSU dataset, amend or create from other datasets if necessary e.g. if the catchment is smaller than covered by the FSU digital data.		
2	Estimate QMED from annual maximum flows	Estimate QMED from catchment descriptors and adjust using ratio from one or more donor sites	Estimate QMED from catchment descriptors
3	Estimate flood growth curve from both single-site and pooled analysis and decide which is more appropriate	Estimate flood growth curve from pooled analysis unless single-site growth curve is preferred at nearby donor site.	Estimate flood growth curve from pooled analysis.
4	Extend flood growth curve for AEPs lower than 1% using ratios from FSR rainfall-runoff method growth curves.		
5	Multiply QMED by flood growth factors from growth curve to obtain design peak flow for each AEP		
6	Derive hydrograph shapes from observed hydrographs and FSR methods and decide which is more appropriate.	Derive hydrograph shapes from FSR rainfall-runoff method with Tp adjusted using lag analysis if results available at donor. Or – use hydrograph shape derived at donor if observed shape preferred there.	Derive hydrograph shapes from FSR rainfall-runoff method, with time to peak estimated from catchment descriptors.
7	Scale hydrograph shape so that the peak flow matches that calculated at step 4, for each AEP.		

7.2 Summary of approach followed at each AFA

Table 7-2 lists the methods that have been applied at each AFA to estimate QMED, the flood growth curve and the design hydrograph shape. It includes the reference numbers of donor or pivotal gauging stations that have been used to adjust QMED or provide hydrograph shapes. In some cases, different methods have been used for different watercourses or different hydrological estimation points (HEPs). The table provides a summary of the various methods used in such cases. A more detailed audit trail of the calculations is available in the digital deliverables, which provide information on the method used at each individual HEP, including those on MPWs which are not listed in the table below.

Table 7-2: Methods used to estimate design flood hydrographs at each AFA

AFA	Watercourse	QMED method	Growth curve method	Distribution	Hydrograph shape
Oranmore	Carrowmoneash, Ballynageeha, Rocklands, Moneyduff	CD (altered from DT – Pivotal 29004)	P	GL	RR
Athenry	Graigabbey River	CD (altered from DT – Pivotal 29004)	P	GEV	RR
Loughrea	St Clearan's River and Lough Rea outlet channel	n/a: Design flood hydrographs downstream of Lough Rea outlet to be estimated using the FSR rainfall-runoff method, routed through the lough.			
	Tonaroasty (tributary that does not discharge from lough)	DT – Pivotal 29007	P	GL	RR
Gort	River Gort, Ballyhugh	To be confirmed in hydraulics report	P, to be confirmed	GL, to be confirmed	RR, to be confirmed

Meaning of codes:

QMED methods - Data Transfer (DT)[8] / Catchment Descriptors (CD)

Growth curve method - Pooled (P) / Single Site (SS)[9]

Distribution - General Logistic (GL) / Gumbel (G) / Generalised Extreme Value (GEV)

Hydrograph shape – FSR rainfall-runoff (RR) / FSR rainfall-runoff with Tp(0) adjusted from lag analysis (RR-LAG) / FSR rainfall-runoff with Tp(0) adjusted to match HWA results (RR-ADJ) / hydrograph width analysis from observed events (HWA)[10]

[8] DT – If data transfer method adopted, pivotal station chosen is detailed

[9] SS – If single site method adopted, station number for which the growth factors have been derived is detailed

[10] HWA – If hydrograph width analysis adopted, station number for which the hydrographs have been analysed is detailed

8 Applying design flows to the river models

8.1 Introduction to the issues

Inflows for the river models will be specified in accordance with the guidance developed for FSU WP 3.4. As hydrodynamic models are being used to represent the rivers, there is the potential for conflicts between the flow simulated by the river model (routed from hydrological inputs applied at the upstream model limits) and the design flows estimated by hydrological methods. In modelling a flood event of a given probability throughout a river system, there is no guarantee that hydrographs scaled to match design flows at model inflows will result in the preferred design flows being reproduced further downstream within the model.

The report on WP 3.4 suggests that the following four factors should be considered when assessing how to apply design inputs to a river model:

1. The extent of the model (for example, whether it includes just one watercourse or extends up its tributaries as well).
2. The presence of gauging stations close to points of interest within the model.
3. The degree of dependence between the upstream and downstream ends of the model, and between any tributaries (or non-modelled inflows) and the main river.
4. The importance of backwater effects.

8.2 Approach adopted for the CFRAM

This section sets out the approach that is expected to be applied when carrying out design runs of hydraulic models. This work is still under way and so the final approach may change, and readers should refer to the hydraulic modelling reports for a record of the method that is finally adopted.

When the extent of a model is short, i.e. there is little change in catchment area along the model reach and little opportunity for attenuation, then setting inflows to the model is expected to be straightforward (apart from perhaps on some small urban watercourses where flows may be affected by hydraulic constrictions such as culverts). This is the case for many model reaches covering HPWs flowing through AFAs, including some in UoM 29. The inflow to the model will be set to the design flood hydrograph for the corresponding HEP, and the peak flow at key points within the model will be checked against design flows for the corresponding HEPs. Significant discrepancies, while considered unlikely, will be investigated and corrected as appropriate through the hydraulic modelling process by applying additional lateral flows where appropriate.

Longer model reaches on MPWs such as the Kilcolgan and Clarinbridge Rivers provide more opportunities for changes in flow due to interactions between tributaries or attenuation. As suggested in the FSU guidance, the first step will be to model a design run of the entire MPW model, with inflows set as described below. If this does not give an adequate representation of design peak flows and flood durations throughout the model reach, we will divide the model into several reaches, each of which will be run separately.

When there are confluences within model reaches where both watercourses contribute a significant proportion of the downstream flow (in particular, at Oranmore), design flows will be set initially using the exceedance probabilities given in the FSU guidance, which depend on the degree of similarity between the catchments of the main river and the tributary. Where necessary, additional lateral inflows will be applied to keep the modelled flow in the river at a realistic value on long model reaches where there are no major confluences. Lateral flows have been developed where required using the FSU methodology to achieve flows at HEP points.

The relative timings of inflows will be specified using the FSR rainfall-runoff method since it has been found that it gives a more realistic representation of hydrograph shapes for ungauged inflows (Chapter 6).

9 Assumptions and uncertainty

9.1 Assumptions

The hydrological analysis relies on a number of general assumptions, which have been necessary given the requirement to estimate design floods for large numbers of locations and for probabilities that include very rare events. Through the study it has been possible to test and refine many of these assumptions. The principal assumptions that remain are:

9.1.1 Assumptions regarding data

The design flows rely heavily on the availability and quality of flood flow datasets. At rating review gauges, it has been possible to check the quality of the flow measurement and (for most gauges) extend the rating up to high flows. However, rating reviews were not carried out at any gauges in UoM29.

- At Clarinbridge, Craughwell and Kilcolgan it is assumed that the existing rating can be relied on up to the highest observed flows. These gauges were not identified for rating reviews.

The potential negative effect of the above assumption has been reduced at Clarinbridge by estimating the growth curves via pooled analysis, which helps to dissipate the effect of any errors in individual flood peak series. However, at Craughwell and Kilcolgan the flood frequency curve has been estimated by single-site analysis. The assumption of a reliable rating is particularly brave at Craughwell as this gauge is classified as grade B in the FSU dataset (whereas Kilcolgan is grade A1). The single-site growth curve at Craughwell has been adopted for estimation of design flows at nearby locations on the Loughrea to Galway Bay MPW model of the Kilcolgan and St Clearan's Rivers. However, neither Craughwell nor Kilcolgan single-site curves have been used to estimate flows at any AFA.

9.1.2 Assumptions regarding hydrological processes

- It is assumed that hydrological processes that operate during extreme floods (down to an AEP of 0.1%) are similar to those that govern more moderate floods that have occurred during the period of gauged records.
- Additional assumptions may be made about processes at Gort, to be confirmed in the hydraulics report once the design flows have been finalised.

9.1.3 Assumptions regarding methods of hydrological analysis

- At Loughrea, it is assumed that the FSR rainfall-runoff method, applied with a routing calculation, gives a more certain estimate of the design flow than accounting for the influence of the lough in a generalised way using the FARL term in the FSU regression equation for QMED.
- For small ungauged catchments, it is assumed that the error introduced by adjusting QMED using a much larger donor catchment will be greater than the benefit (in terms of standard error) of applying the adjustment, and so QMED has been estimated solely from catchment descriptors on such catchments.
- It is assumed that, for the majority of AFAs, the FSR rainfall-runoff method gives a more realistic hydrograph shape than the FSU ungauged catchment method, with or without adjustment using a pivotal site. This assumption has been tested at a set of example catchments as discussed in Chapter 6.

9.2 Uncertainty

The brief for the CFRAM requires degrees of confidence to be presented in the mapped flood outlines. Flood frequency estimates are inherently uncertain because they cannot be measured or formally validated against observed data.

For the Western CFRAM, design flood hydrographs have been developed for a wide range of flood AEPs (down to 0.1%, corresponding to a return period of 1000 years) and for a large number of locations. There is inevitably a large degree of uncertainty in the results, particularly at ungauged locations and for low AEPs. It is important that the results produced in this study are not taken as the final word on flood frequency for the Western RBD. The uncertainty in the design flows is likely to be the largest source of the uncertainty in the modelled water levels and mapped flood outlines produced in the CFRAM study.

This uncertainty can be broken down into different components:

- **Natural uncertainty**, from the inherent variability of the climate.

  This is a substantial source of uncertainty. The longest record of flood peak data that has been analysed in UoM 29 is 37 years, at Clarinbridge. Some of the pooling groups include longer records, up to around 60 years in some instances. There is a great deal of uncertainty in extrapolating from these relatively short records to estimate design flows that are expected to occur once in 100 or 1000 years on average.

  Natural uncertainty can be classed as *aleatory*. Aleatory uncertainty describes the random occurrence of values about a mean that can be appropriately described by a probability distribution; as a result confidence intervals can be assigned to this distribution and associated with mapped outputs.

- **Data uncertainty**, from the measurement of flood flows. As discussed above under assumptions, the degree of uncertainty in the rating equations within UoM 29 has not been tested within the CFRAM study.
- **Model uncertainty**, which includes aspects such as the choice and fitting of flood frequency distributions and the application of ungauged catchment methods such as the regression equation for estimating QMED and the procedures for defining hydrograph shapes.

  The uncertainties associated with data measurement and models or analysis techniques can be classed as epistemic, i.e. associated with knowledge. Some sources of epistemic uncertainty describe variation that do not occur randomly and so cannot be described probabilistically. It is therefore difficult to assign limits to this uncertainty as the true range of values can vary widely.

There is an increasing desire to see uncertainty discussed and presented in flood mapping and assessment investigations. However, many of the uncertainties in this work are epistemic and confidence intervals based on probability distributions cannot be derived. A recent publication[11] suggests it might be better to represent such uncertainties "possibilistically". This can be done through scenarios or sensitivity testing.

In considering how to assess uncertainty for use on the CFRAM it is important to understand where probability distributions can be applied to uncertainty and where sensitivity tests need to be used to investigate uncertainty.

Quantifying uncertainty

It is possible to quantify some elements of uncertainty. Where an index flood approach is applied to derive design flows, uncertainty can in theory be assessed on the two components used in the development of the hydrology, the index flood (QMED for the FSU method) and the growth curve.

The standard error (SE) is a measure used to describe uncertainty about an estimate of something, when the estimate is based on the data in a sample. It represents only the aleatory uncertainty and does not account for any possible bias in the procedure for estimating design flows – for example due to the selection of a pooling group that is not truly representative of the hydrological behaviour of the subject catchment.

Factorial standard error (FSE) is a term used occasionally in flood hydrology to describe errors from an estimate made from a multiplicative process, such as the regression equation that

11 Framework for Assessing Uncertainty in Fluvial Flood Risk Mapping, Flood Risk Management Research Consortium Research Report SWP1.7, 2011.

estimates QMED from a multiple of catchment descriptors. These two measures of uncertainty in a design flow Q are related thus:

FSE = 1+ (SE/Q)

The uncertainty in QMED can be assessed using the equations for SE and FSE provided in the FSU WP2.2 report. These are provided for estimates derived from catchment descriptors or at gauge sites:

- For QMED estimated from catchment descriptors: FSE=1.37
- For QMED estimated from N annual maximum flows: SE = 0.36/√N

So for many small ungauged HEPs, where no suitable donor catchment could be found, the FSE in QMED is 1.37. For HEPs at gauging stations, the FSE for UoM 29 is 1.06 to 1.07.

In discussing the standard error of pooled growth curves, the FSU WP2.2 report (Section 13.3) states that the uncertainty in the design flow for any return period is dominated by the uncertainty in QMED. This result differs from the findings of research elsewhere (such as Kjeldsen and Jones, 2006[12]). While the difference may be due to the unusually low skewness of Irish flood datasets, there is a risk that the overall uncertainty in design flows could be underestimated if it is assumed that even for very long return periods the factorial error is similar to that calculated for QMED. However, for the purpose of this study the findings of the WP 2.2 report will be taken at face value, and hence calculation of uncertainty in design flows estimated from pooled analysis will be limited to the consideration of factorial errors in QMED.

The standard error for single-site flood frequency curves (which have been applied at two gauges in UoM 29) has been estimated using theoretical expressions given in the FSU WP2.2 report (Section 13.2). When a Gumbel distribution is fitted, the SE depends on the scale parameter, the number of annual maximum flows and the return period. The scale parameter is that for the flood frequency curve, not the flood growth curve which is what is shown in Appendix B. The resulting standard errors, for the 100-year return period are:

- At Craughwell (scale parameter 6.84): the SE for the 1% AEP flood is 5.9m^3/s. This is 10% of the 1% AEP design flood.
- At Kilcolgan (scale parameter 7.62): the SE for the 1% AEP flood is 6.6m^3/s. This is 11% of the 1% AEP design flood.

Confidence intervals

If it can be assumed that factorial errors in design flows are normally distributed, the factorial error can be used to construct approximate confidence intervals for the design flows. The 95% confidence interval for QMED, i.e. the range in which we are 95% confident that the true value of QMED lies, is equal to (QMED/FSE^2, QMED.FSE^2).

Therefore 95% confidence intervals for the estimated design peak flow Q where derived from pooled growth curves are as follows:

- 0.89Q to 1.12Q for HEPs at (or very close to) Clarinbridge gauge
- 0.54Q to 1.85Q for ungauged HEPs with no donor adjustment applied

It is important to realise, as discussed above and below, that these represent only part of the uncertainty in the design flows.

For ungauged HEPs where a donor adjustment has been applied, the confidence interval can be expected to lie somewhere between the values for gauged and ungauged sites. This is obviously a very large range. The nearer the HEP to the gauge along the river network, and the more similar the catchments, the closer will be the confidence interval to that which applies at the gauge. The FSU research did not produce any statistical model that could be used to quantify how the uncertainty in QMED estimation reduces as a result of applying a donor adjustment, and so, without additional research, any attempt to quantify the uncertainty for ungauged HEPs where a donor adjustment has been applied would be subjective and open to challenge.

[12] Kjeldsen, T.R. and Jones, D.A. (2006). Prediction uncertainty in a median-based index flood method using L moments. Water Resources Research 42, W07414.

By the same method, 95% confidence intervals for the 100-year design flow Q estimated from single-site growth curves are:

- 0.83Q to 1.21Q for HEPs at (or very close to) Craughwell gauge.
- 0.81Q to 1.23Q for HEPs at (or very close to) Kilcolgan gauge.

These confidence intervals do not make the assumption that the FSE is invariant with return period, and thus may be a fuller description of the uncertainty than those given above for pooled growth curves. However, they do not include any allowance for bias in the estimation procedure or for errors in the rating curves, to which single-site flood estimates are particularly sensitive.

Sensitivity testing

Other sources of uncertainty cannot be easily quantified. There is scope to examine some of them through sensitivity testing. This has been carried out in aspects of the analysis, for example by comparing growth curves fitted using different distributions (Appendix B), QMED adjusted using different donor gauges or design flood hydrographs derived using different methods (Chapter 6).

Further sensitivity testing will be carried out as part of the hydraulic modelling work to quantify the effect that these quoted bounds of uncertainty have on the predicted extent of flood risk.

10 Design sea levels

10.1 Synopsis

This chapter details the methodology of work undertaken to produce design tidal curves on the coast of the Western RBD. Tidal graphs are required at the downstream boundary of the MPW hydraulic models, and at the boundary of the Kinvarra coastal model. Where screening has identified the potential for wave overtopping, such as in Kinvarra, inflows to the overtopping model are also required.

The work described in this chapter covers the whole of the Western CFRAM study area.

10.2 Design tidal graphs

A design tidal graph is a time-series that quantifies how sea-levels are expected to change through time during an extreme event. It is these design tidal graphs that are used to drive the still water component of the flood inundation model at its offshore boundaries. Creation of design tidal graphs requires three principal sources of information: an extreme sea level (ESL) estimate for the return period of interest; a design surge shape, and; a design astronomical tide.

Initial assessments were made into the data available for the three required sources and the most relevant source locations were selected respective to each study site shown in Table 10-1.

Table 10-1: Locations of data sources required for the design tidal graphs

Model location	HAT tide gauge	ESL data point location code	Surge profile
Westport	Inishgort	W41	Inishgort
Galway	Galway	W6	Galway
Kinvarra	Galway	W3	Galway
Sligo	Sligo Harbour	NW6	Sligo
Ballysadare	Sligo Harbour	NW6	Sligo
Ballina	Killala Bay	NW1	Sligo
Newport	Inishgort	W42	Inishgort
Louisburgh	Roonah Bay	W39	Inishgort
Clifden	Bofin Harbour	W29	Inishgort
Roundstone	Roundstone Bay	W23	Galway

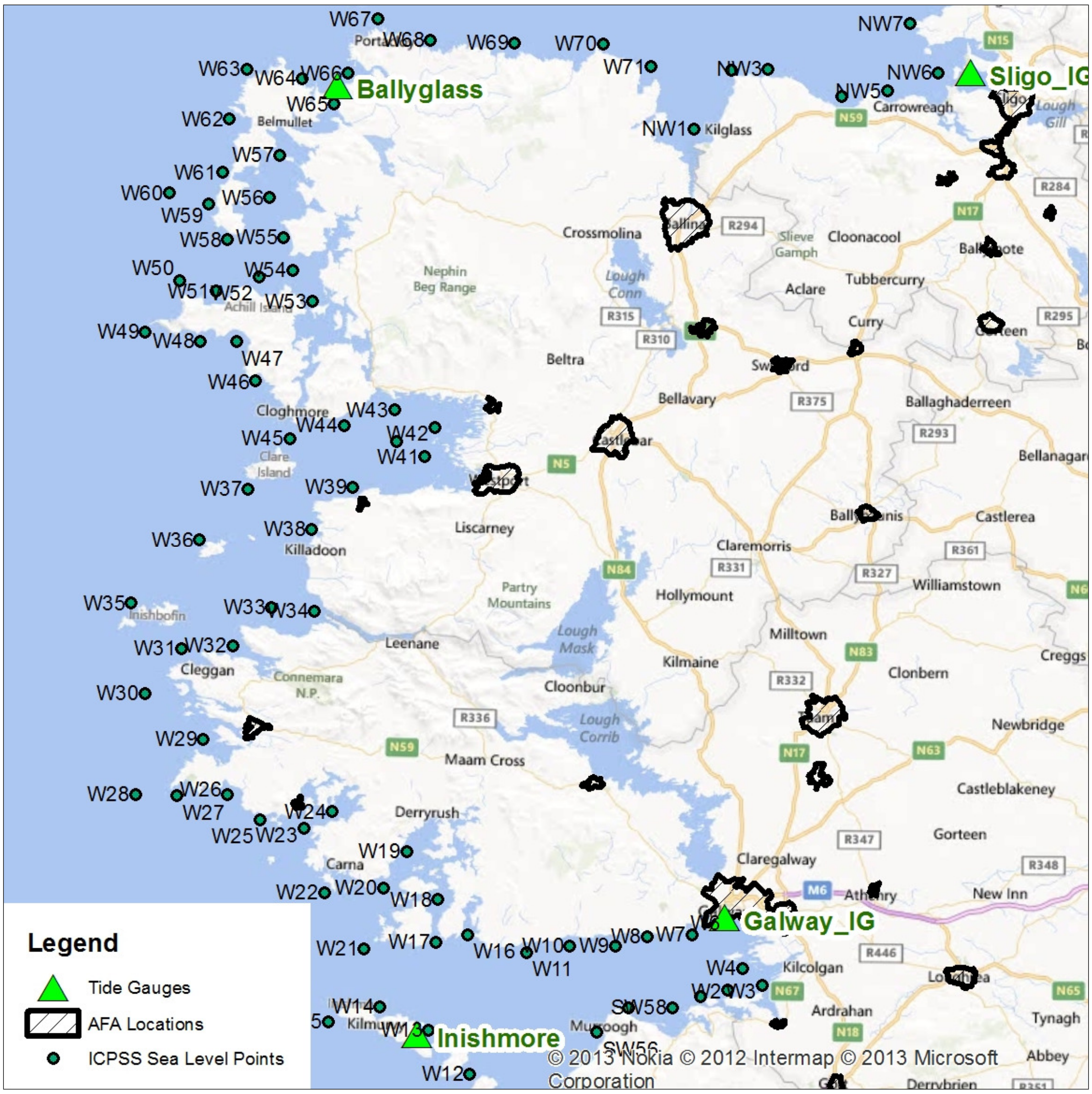
The ESLs used in the derivation of the design tidal-graphs were taken from the Irish Coastal Protection Strategy Study Phase 3 - West Coast[13] report; shown in Table 10-2 and Figure 10-1. These were based on a global tidal model developed by Kort and Matrikelstryreslen in Denmark.

Table 10-2: ESLs (mOD) for each respective study site

	Return Period (years)							
Location	**2**	**5**	**10**	**20**	**50**	**100**	**200**	**1000**
Westport	2.79	2.96	3.09	3.21	3.37	3.49	3.61	3.88
Galway	3.06	3.21	3.32	3.42	3.56	3.67	3.77	4.02
Kinvarra	3.17	3.31	3.40	3.50	3.62	3.71	3.80	4.02
Sligo	2.50	2.64	2.73	2.82	2.94	3.03	3.12	3.33
Ballysadare	2.50	2.64	2.73	2.82	2.94	3.03	3.12	3.33
Ballina	2.44	2.56	2.64	2.72	2.8	2.91	2.99	3.18
Newport	2.85	3.03	3.16	3.29	3.46	3.58	3.70	3.99
Louisburgh	2.76	2.92	3.04	3.15	3.30	3.41	3.53	3.79
Clifden	2.69	2.83	2.94	3.04	3.17	3.27	3.37	3.60
Roundhouse	2.80	2.96	3.07	3.18	3.33	3.43	3.54	3.79

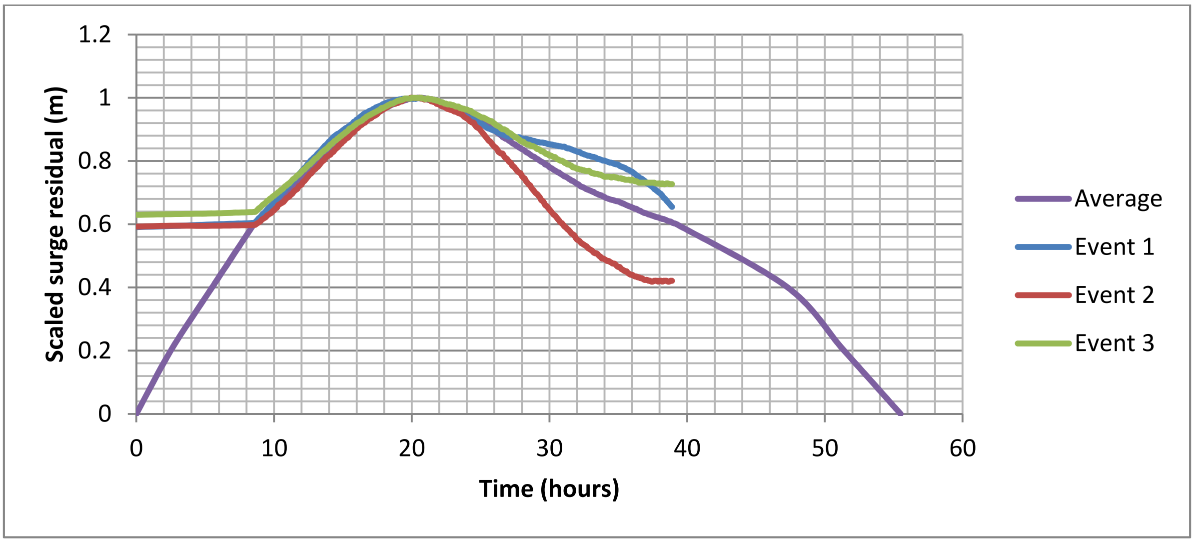
[13] OPW, 2011, Irish Coastal Protection Strategy Study Phase 3 – West Coast

Figure 10-1: West Coast ICPSS sea level points and tide gauges



Design surge profiles were derived from analysis of storm surge residuals supplied by the Marine Institute. The surge residuals from the largest three storm events (i.e. those resulting in the highest water level) were first identified. These three surge profiles were then normalised so all surge profiles peaked at one and then the average of these three profiles produced the design surge profile at each gauge. An example surge profile from Ballyglass is shown in Figure 10-2. Many of the large surge profiles were taken from periods of protracted storminess, leading to long periods of time with elevated surge residuals. In Figure 10.2 the surge residuals below 0.6m begin to plateau, therefore, to enable the extraction of a discrete surge profile for the design events, the levels below 0.6m were interpolated down to zero.

Figure 10-2: Surge profile analysis at Ballyglass



The underlying tide that will be used in the derivation of the design tidal graphs is the highest astronomical tide (HAT) profile, as predicted by the Admiralty Total Tide Software. Prediction sites recognised in Table 10-1 were extracted from the Total Tide software, with levels given to local chart datum.

With the above information collated, the design tidal-graphs were constructed by combining the design astronomical tide with the design storm surge. The peak of the storm surge was situated such that it occurred at low tide; this results in a more conservative tidal-graph, i.e. with a greater volume, than if the peak of the surge profile was situated at high tide. To demonstrate this it can be seen from Figure 10-3 that the overall volume of the design tidal curve is increased more if the peak of the surge is aligned with a trough of the underlying tidal series, than if it was scaled to the peak of the tide. Effectively the peak of the event occurs on the falling limb of the surge resulting in a flatter, more prolonged tidal event as the peak of the surge passes through before the peak of the event.

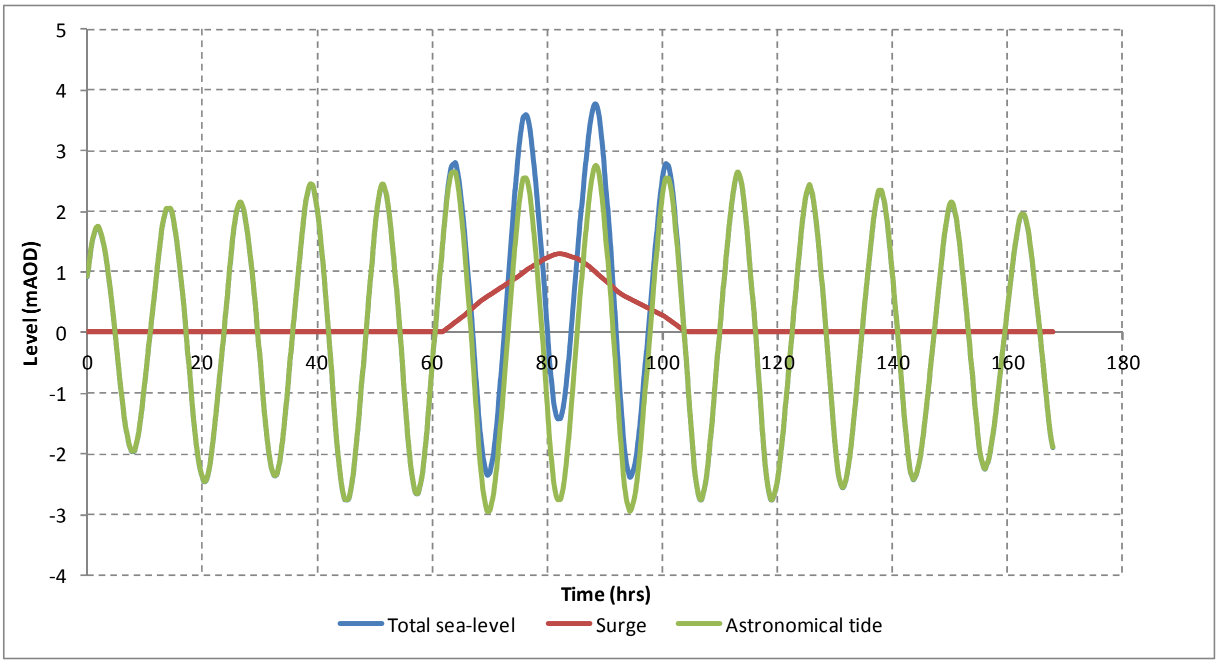
The design tidal curves were then corrected from Chart Datum, through Ordnance Datum Poolbeg, to Ordnance Datum Malin Head. In recognition of the complexity of translating through three different datums, a secondary correction factor of -0.15m or -0.1m was calculated in the Irish Coastal Protection Strategy Study, and was applied to the design tide curves. Table 10-3 shows the datum correction used at each study site. These corrections were applied so that the ESLs and tide data were in the same datum. The secondary correction is to allow for an error in the Malin datum correction that has been identified by the Irish Coastal Protection Strategy Study.

Table 10-3: Datum corrections used at study sites

Model location	From chart to Ordnance datum Poolbeg (m)	From Ordnance datum Poolbeg to Malin Head (m)	Secondary corrective (m)
Westport	0.11	-2.71	-0.10
Galway	-0.20	-2.71	-0.15
Kinvarra	-0.20	-2.71	-0.15
Sligo	0.69	-2.71	-0.15
Ballysadare	0.69	-2.71	-0.15
Ballina	0.72	-2.71	-0.15
Newport	0.11	-2.71	-0.10
Louisburgh	0.11	-2.71	-0.10
Clifden	0.00	-2.71	-0.10
Roundstone	0.00	-2.71	-0.15

As an example, the present day design tidal graph derived for a 0.5% AEP event for Galway is shown in Figure 10-3.

Figure 10-3: Design tidal graph at Galway for a 0.5% AEP



10.3 Wave overtopping analysis

Wave overtopping has not been assessed at this stage of the project but will be covered under the hydraulics reporting.

10.4 Joint probability analysis

Joint probability analysis of the tidal and fluvial interactions has not been assessed at this stage of the project but will be covered under the hydraulics reporting.

11 Future environmental and catchment changes

11.1 Introduction

Specific advice on the expected impacts of climate change and the allowances to be provided for future flood risk management in Ireland is given in the OPW draft guidance[14], which calls for estimation of design flood parameters for two future scenarios, each intended to be a possible representation of flood conditions in 100 years time, i.e. around the year 2110:

- The Mid-Range Future Scenario (MRFS) is intended to represent a 'likely' future scenario, based on the wide range of predictions available and with the allowances for increased flow, sea level rise, etc. within the bounds of widely accepted projections.
- The High-End Future Scenario (HEFS) is intended to represent a more extreme potential future scenario, but one that is nonetheless not significantly outside the range of accepted predictions available, and with the allowances for increased flow, sea level rise, etc. at the upper bounds of widely accepted projections.

The scenarios encompass changes in extreme rainfall depths, flood flows, sea level, land movement, urbanisation and forestry. The allowances for each of these aspects, apart from urbanisation, are set out in the brief. The sections below set out how design flood parameters for the future scenarios have been defined.

11.2 Impact of climate change on river flows

The guidance states that flood flows shall be increased by 20% and 30% respectively for the MRFS and HEFS. This change has been implemented by scaling up the flood hydrograph for each HEP and for each probability by the specified percentage.

11.3 Impact of urbanisation

For urbanisation the approach adopted for the Western CFRAM is to calculate future urban growth patterns based on the core strategy for each county, which is in turn based on the settlement hierarchy detailed in the National Spatial Strategy (NSS)[15]. Although the plans and strategies do not extend to the 100 year horizon, they give an indication of where development is to be targeted for the plan period, which can be interpreted to be the likely focus of growth for the future.

The settlement hierarchy, as laid out in the NSS, has been reviewed, and the classification of each AFA in UoM29 is shown in Table 11-1. Within the Western CFRAM area there are two gateways (Galway City and Sligo Town, including Oranmore and Willowbrook respectively), three hubs (Tuam, Ballina and Castlebar) and six smaller settlements which have been identified as having urban strengthening opportunities. It is in these 11 AFAs that urban growth will be focused over the plan period, and then over the next 100 years. An analysis of the Core Strategies for Galway City and County has shown a potential increase in housing land requirement of between 8 and 20%, based on the land shown as currently urban in the CORINE data set. In Sligo, development requirements are centred on Sligo town and environs, with a housing land requirement of 40 ha compared with 195ha across County Sligo; this target is centred largely on non-AFA settlements. A similar pattern of development requirement is seen in County Mayo, with a focus on the hubs of Ballina and Castlebar.

When reviewing the above analysis, the following should be borne in mind:

- No clear pattern was identified linking the percentage housing allocation to the rank of the settlement in the hierarchy.
- The housing land targets span only the period to approximately 2020 (depending on the dates of the relevant Development Plan).

[14] OPW Assessment of Potential Future Scenarios, Flood Risk Management Draft Guidance, 2009

[15] National Spatial Strategy for Ireland 2002-2020. The National Stationary Office

- The Development Plans themselves acknowledge that the land requirements are a conservative estimate (allowing for some 50% over zoning for market choice in development).
- Whilst it is possible to draw conclusions about the patterns of growth over the next 100 years, the scale of this growth is not known.
- All development plans include the requirement for SUDS to be included in new builds, so run off and flood generating potential should be reduced into the future.
- The aim of the guideline document, The Planning System and Flood Risk Management is to ensure flood risk does not become unmanageable within a catchment; over future development plan periods, SFRAs will be undertaken which will assess and reassess flood risks presented by planned development, and ensure those risks remain manageable.

Table 11-1 NSS Settlement Hierarchy

AFA	ID	County	NSS classification
Oranmore	290490	Galway	Not listed specifically - include with Galway City
Kinvarra	290487	Galway	No classification
Loughrea	290489	Galway	Town (1,500-5,000) with urban strengthening opportunities
Athenry	294227	Galway	Town (1,500-5,000) with urban strengthening opportunities
Gort	294338	Galway	Urban Centre (circa 1000) – urban strengthening opportunity

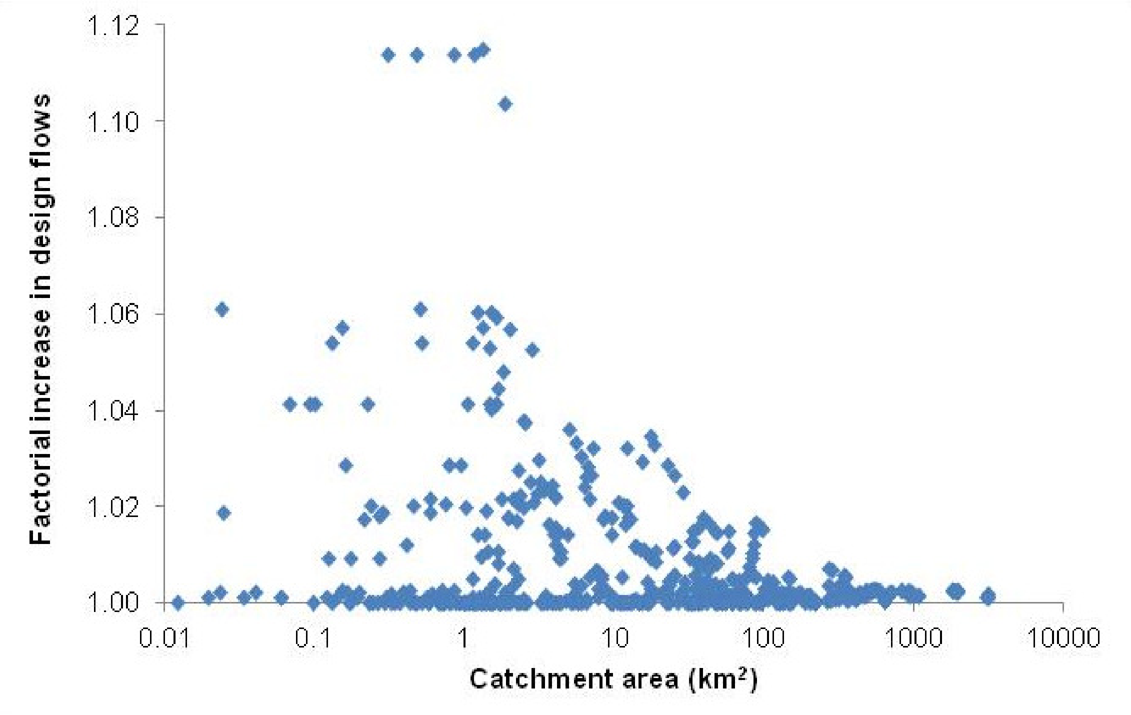
Future design flows have been tested using a future URBEXT value which is based on a percentage increase of the current URBEXT value, and then applying the urban adjustment formula developed in Flood Studies Update WP 2.3. The calculation involved first removing the effect of current urbanisation, converting the design flows to as-rural values, and then adding the effect of the possible future urbanisation. It should be noted that most methods that allow for the effect of urbanisation on design flows, including both the adjustment for QMED in the FSU and the allowances for time to peak and percentage runoff in the FSR rainfall-runoff method, are based on analysis of flood data from existing urbanised catchments. Most of these catchments include a wide range of development types, ranging from old town centres with no runoff mitigation measures to recent developments with SUDS or other measures aimed at restricting the runoff from the developed area. The downstream flooding impacts of future development should be minimised and so it is to be hoped that the allowances for the impact of urbanisation on future design flows represent a conservative worst case scenario.

For the majority of catchments the increase in flows is extremely minor, or non-existent, as the existing urban proportion is extremely small, with little increase in QMED seen regardless of the scale of future urbanisation. Therefore for the MRFS a uniform 20% growth to URBEXT for all catchments has been applied, reflecting the maximum increase shown in the analysis of the core strategies, but recognising the capping factors on increases in flood risk discussed above. The maximum anticipated increase in QMED in this scenario is a factor of 1.11. The resulting increases in design flows are illustrated in Figure 11-1, which plots the factorial change in QMED (and hence in design flows for all AEPs) at every HEP in the Western CFRAM. The changes are plotted against catchment area, on a logarithmic scale. The plot shows how the application of a uniform increase in URBEXT results in a variable shift in flows; those catchments with a higher URBEXT value initially show the greatest increase in flows following the adjustment.

For the HEFS it is recommended that a uniform 30% growth to URBEXT is applied; this value has not been derived from the available data as described above but represents a conservative assumption in relation to the MRFS given the uncertainties associated with extrapolating this data over the 100 year time frame.

No change in the timing of the peak of the event as a result of the impact of urbanisation has been assessed. However the sensitivity of the models to changes in timings of the hydrographs is explicitly investigated within the hydraulic modelling reports.

Figure 11-1: Increases in design flows at each HEP as a result of future urbanisation



11.4 Impact of changes to forestry management

Changes to forestry management in a sub-catchment, either through deforestation or afforestation, can potentially influence flood risk by affecting surface water runoff. For the purposes of the Western CFRAM study the focus of interest is on the changes in practise that will in time result in an increase in flood risk downstream. This understanding will be used to inform the MRFS and HEFS.

Under the MRFS scenario outlined in the project brief, it is recommended that the impacts of afforestation are investigated through a decrease in time to peak of a sixth; this allows for potential accelerated runoff that may arise as a result of drainage of afforested land. This means the volume of water in the river is unchanged, but the rate at which it runs off the land into the watercourse is increased. The change in the time to peak can also have a positive or negative impact on flood risk depending on how it relates to the timing of peak runoff from contributing watercourses further downstream in the catchment.

Although the theory of forests acting as sponges soaking up water is popular, scientific studies have shown that the influence of forests on flooding and runoff is more complex[16]. Most of the well-known experimental hydrological studies of forestry have been undertaken in the UK, and have been on upland catchments, primarily investigating plantation forestry. In such cases, the effects of the forestry on runoff have been complicated by the influence of drainage ditches dug before the trees were planted.

Perhaps because of the complications of the crop cycle and management practices (such as drainage), there is little evidence from regional flood studies that the area covered by forest is a significant independent variable in the regression equations used for flood estimation[17]. However, this does not mean that forests have no effect on a local scale. Forests and forest soils (with their deep litter layer) are capable of storing and transpiring more water than grassland or arable crops. Therefore where afforestation is occurring within a catchment, and in the absence of complicating factors such as drainage, one can expect a reduction in downstream flood volumes and an increase in time to peak.

[16] UNFAO Center for International Forestry Research (2005). Forests and Floods. UNFAO.

[17] Institute of Hydrology (1991). Plynlimon research: The first two decades. Report No. 109, Institute of Hydrology.

Applying the proposed MRFS changes to reflect the impact of afforestation globally to all HEPs across the study area will have a significant impact on peak flows, but this approach does not consider the spatial distribution of forests or the potential variability in runoff response over time across the Western CFRAM. Therefore to better understand the risks presented by changing land use patterns in the Western CFRAM area and to determine a more appropriate approach to the representation of changes in forest management in the MRFS and HEFS, a review of the distribution of the catchment characteristic 'FOREST' has been carried out. Although the area is largely rural, forestry practice is limited and is generally located in the upper parts of the river catchments, and tends not to form a large proportion of the land use on major rivers which flow through most of the AFAs.

Rather than apply a uniform adjustment factor to account for the impact of forestry, an analysis of each catchment has been carried out immediately upstream of the AFA. This reflects the fact that small scale changes in the upper catchments may not have an impact at the AFA downstream and often on a larger and less responsive river. Adopting a non-uniform approach also ensures that catchments which are largely urban are not also subject to forestry related changes in flow.

The HEPs upstream of an AFA were divided into three bands; those with a FOREST value of less than 25, 25-50 and over 50. Where FOREST is under 25 it was determined unlikely that any changes in forestry management would generate significant changes in flood risk, and certainly it would not be possible to say that any changes that were to occur would be linked to forestry; it is more likely that changes in arable farming practice or urbanisation would take place. A FOREST value of 25-50 shows a greater current forest cover, but one which is a combination of native woodland and managed conifer forests. Although changes to forest management practice in these catchments will occur, it is unlikely that sweeping changes would arise; instead the phased nature of forestry means that while some areas are cleared, others in the catchment are growing, thus balancing the impacts of drainage and felling. Whilst the changes in forestry management practices occurring in catchments with a FOREST value of greater than 50 are unlikely to have a combined significant impact, it was considered that there was enough of a potential impact to warrant further investigation. The only catchment where this was the case was in UoM35, and the impacts have been discussed in the relevant hydrology report.

It is therefore concluded that in UoM 29 (and all others except 35) the likely impact of changes in forestry management practices are so uncertain, and relate to such a relatively small catchment area that the impacts should be excluded from the development of the future scenarios.

11.5 Sea level rise and land movement

Changes in sea and land levels in the Western CFRAM have been set out by the OPW at a national scale and no catchment specific changes are proposed as would be expected in these instances.

Sea level rise will be assessed by increasing levels by 0.5m and 1m in the MRFS and HEFS respectively. Land movement changes are only applicable for coastal sites south of the Galway to Dublin line; therefore this will apply to Kinvarra only. Land movement is assessed at a reduction in levels of 0.5mm/yr for both the MRFS and HEFS, which equates to 50mm over the 100 year time frame. This shift will be applied on top of the changes in sea levels described above.

11.6 Results: future flows

Design flows for the two future scenarios have been obtained by adjusting the present-day design flows, applying in combination the factors representing increases due to climate change and urbanisation but discounting forestry.

The overall factorial changes in design flow fall within the following ranges:

- For the Mid-Range Future Scenario (MRFS): from 1.20 to 1.34
- For the High-End Future Scenario (HEFS): from 1.30 to 1.53

Design peak flows at each HEP for both future scenarios are provided in Appendix F and with the digital deliverables associated with this report.

Associated with these flows, increases in sea levels of 0.5m and 1.0m will be applied for the MRFS and HEFS respectively. For Kinvarra and additional 0.05m will be applied in each case to account for land movement.

12 Digital deliverables

12.1 Datasets provided with this report

Appendix F provides a table that lists the location of each HEP and the design peak flows for present-day conditions for the full range of HEPs. The table also provides a summary of how the flows were derived, i.e. the adjustment factor for QMED, the choice between a single-site or pooled growth curve and the distribution chosen for fitting the growth curve.

To avoid filling up the report with numerous long tables and to aid searching and copying of the results, more comprehensive results are provided digitally. The report is accompanied by the following digital deliverables:

- Shapefile of catchment descriptors for each HEP:

  This lists all the FSU catchment descriptors at each HEP. The source of the descriptors is recorded via the fields OPW_JBA (which distinguishes between descriptors taken straight from OPW's FSU dataset and those modified at JBA) and Node_ID (which records the name of the node in the FSU dataset on which descriptors have been based). This is relevant for very small catchments that do not appear in the FSU dataset. The AREA descriptor for each small catchment is calculated individually, but most other descriptors may be copied from a nearby FSU node.
- Shapefiles of catchment boundaries for each HEP:

  Catchment boundaries that have been created or modified by JBA are given in shapefiles with a name that corresponds to the label of the HEP. Catchment boundaries that have not been altered from the information supplied by OPW are in shapefiles that use OPW's naming convention (i.e. NODE_ID). A spreadsheet is included to enable cross-referencing between the label of each HEP and the corresponding shapefile NODE_ID.
- Shapefile of present-day design flows for each HEP:

  This gives the peak flows, as tabulated in Appendix F, but also contains more information on how the flows were derived, including the reference number of any gauging station located at the HEP, the reference number of any gauging station nearby whose single-site growth curve has been applied to calculate design flows at the HEP, and information on adjustment factors for QMED and growth curve derivation including FSR adjustment ratios as provided in Appendix F.
- Shapefile of future scenario design flows

Each of the above files covers all of the Western RBD.

In addition to the above the following files, which do not contain outputs from the hydrology study but have been included for information, have been supplied:

- A shapefile containing catchment descriptors for all gauges where catchment descriptors have been updated to reflect changes identified during the study
- A shapefile containing the surveyed watercourses.

Design hydrograph shapes are provided digitally in the form of inflows to the hydraulic models that are being developed.

13 Conclusions and recommendations

13.1 Conclusions

1. Flood hydrology is challenging in unit of management 29 owing to the complications posed by karst (especially around Gort), the influences of water bodies (Lough Rea) and the absence of flow gauges close to the four AFAs where design flows are required. For this reason, design flows are uncertain at all AFAs.
2. Design flows are expected to be more uncertain for low AEPs given the possibility that such extreme floods may arise from physical processes that do not make a significant contribution to events contained in the gauged records.
3. The methods of the Flood Studies Update have proved, in the main, straightforward to apply and suitable for the estimation of design flows on most catchments in this unit of management. However, for design events greater than the 1% AEP, it has been judged appropriate to supplement the FSU methods with growth curves from the Flood Studies Report rainfall-runoff method.
4. Extreme tidal curves have been generated for Kinvarra for use in inundation and wave overtopping modelling.

13.2 Recommendations

Several recommendations are offered at the conclusion of this report:

1. The design flows are suitable for the purposes of the Western CFRAM study, apart from at Gort where further work is currently in progress (to be described in the hydraulics report).
2. For any future improvements to the design flood estimates it is recommended that consideration is given to establishing flow gauging stations at Athenry and Loughrea. At Oranmore it may be that flood risk is predominantly tidal but if there turns out be a significant hazard from fluvial flooding, design flows in the future could be estimated with more confidence if a flow gauge could be established at a site free from tidal influence.
3. At Craughwell and Kilcolgan a review of the rating equations would help to confirm the accuracy of the measurement of the November 2009 flood which has had a significant influence on the estimation of the flood frequency curve at nearby locations on the MPW, Kilcolgan / St Clearan's River. A rating review would be particularly valuable at Craughwell as this gauge is classified as grade B in the FSU dataset

The two final recommendations are on the subject of the FSU methods:

4. It is recommended that further research is carried out aimed at improving the approach to derivation of characteristic flood hydrographs on ungauged catchments. It is difficult to have much confidence in the current method. The addition of a term representing catchment size would be of benefit, as would a study into the optimal way of identifying and using pivotal catchments to transfer information on hydrograph shapes.
5. It is recommended that OPW's recent research on small catchments is extended to examine the benefits (or otherwise) of adjusting QMED using donor/pivotal stations, given that there are rarely any nearby donor stations available on comparably sized catchments.

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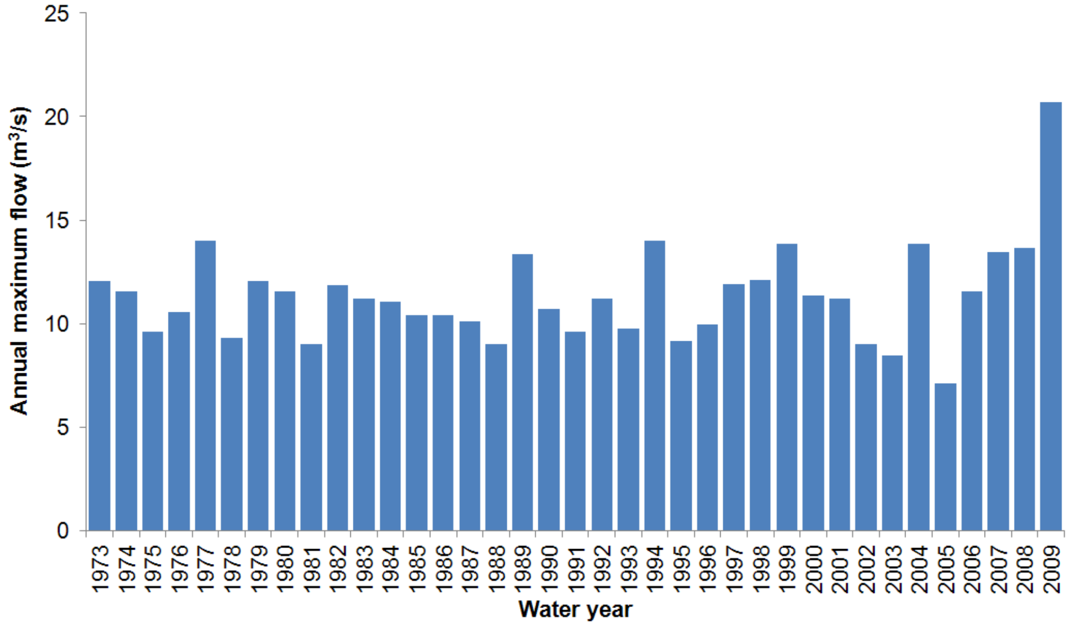
Appendices

A Rating reviews

B Flood peak analysis

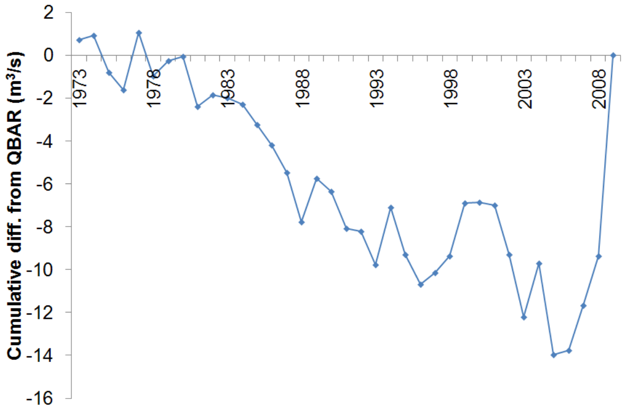
Flood frequency analysis summary sheet

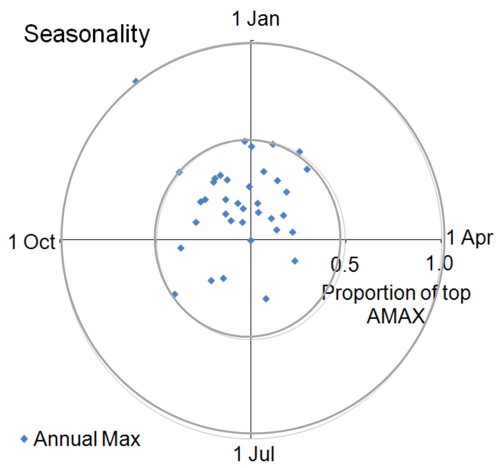
Station 29004	Clarinbridge @ Clarinbridge



Top ranking floods:			QMED (m^3/s): 11.2
Rank	**Date**	**Flow (m^3/s)**	**AEP (%) from single-site analysis**
1	22 November 2009	20.7	0.3
2	29 January 1995	14.0	11.4
3	11 November 1977	14.0	11.4

Tests for stationarity:
Mann-Kendal test: no significant trend

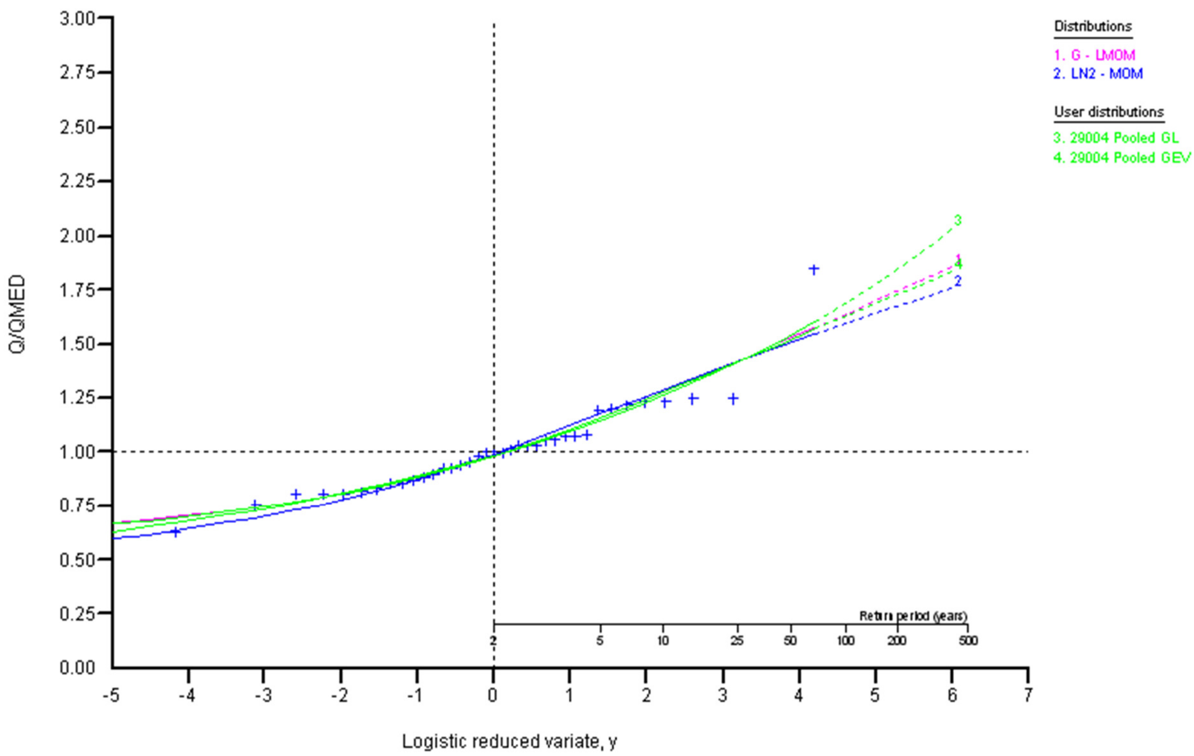




There is a slight bias in seasonality of the AMAX data supplied for this site with the majority of events occurring between October and April despite AMAX flows being observed throughout the year. There is a large range in the magnitude of AMAX floods, although this is mainly due to exceptionally large flows recorded at the peak of the 2009 event. This event has a growth factor of 1.8, much higher than the growth factor of 1.3 associated with the second and third largest recorded floods. There is no significant trend evident within this dataset.

Notes: Annual maxima have been sourced directly from OPW. A rating review was not undertaken for this site.

Flood frequency analysis – comparison of single-site and pooled growth curves



Distribution	Location	Scale	Shape	100-year growth factor
Single-site Gumbel (L-moments)	0.922	0.155	n/a	1.637
Single-site LN2 (moments)	-0.009	0.204	n/a	1.592
Pooled GL (L-moments)	1.000	0.140	-0.087	1.790
Pooled GEV (L-moments)	1.000	0.228	0.135	1.700

Comments on growth curves

There is little difference in any of the fitted flood growth curves. If the analysis had been carried out before November 2009, the single-site growth curves would have been less steep. With the November 2009 flood included, the annual maximum flows at Clarinbridge follow a similar distribution to the rest of the pooling group. As is typical, the GL curve is more skewed than the GEV and thus gives slightly higher estimates of design floods for long return periods.

The AEPs for the top three floods on the first page were derived from the single-site Gumbel, which was selected in preference to the LN2 as it has been found to give an acceptable fit to flood peak data at a larger number of stations in Ireland (FSU work package 2.2).

Recommended growth curve

The pooled GEV is recommended as the preferred growth curve for design flood estimation at this gauge as it gives almost identical results to the single-site Gumbel, while allowing more confident extrapolation of the curve to lower AEPs.

Recommended design flows[1] (Pooled GEV)

[1] Final design flows have been developed from the recommended design flows at gauging station presented here but these have been further modified in some areas through regional smoothing of the QMED adjustment factor. In addition, for all HEPs the flood growth curve was extended for AEPs lower than 1% using ratios from FSR rainfall-runoff method growth curves. Please refer to Appendix F Design flows for the final design flows derived following these additional modifications.

AEP	50%	20%	10%	5%	2%	1%	0.5%	0.1%
Flow (m^3/s)	11.2	13.8	15.2	16.5	18.0	19.1	20.0	21.8
Growth factor	1.0	1.2	1.4	1.5	1.6	1.7	1.8	1.9

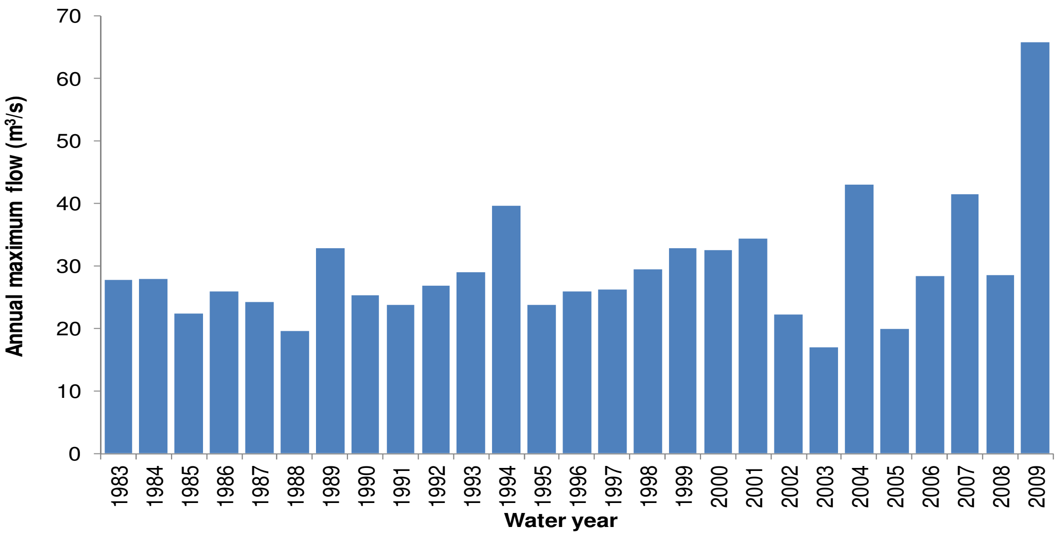
Composition of the pooling group

The stations in the pooling group have been selected as the most similar catchments in Ireland and Northern Ireland according to three descriptors at the subject site: AREA (115km^2), SAAR (1103mm) and BFIsoil (0.62).

ID	Rank	Watercourse	Location	Years
29004	1	Clarinbridge	Clarinbridge	37
25027	2	Ollatrim	Gourdeen Bridge	48
26018	3	Owenure	Bellavahan	54
25044	4	Kilmastulla	Coole	40
25014	5	Silver	Millbrook Bridge	55
26001	6	Shiven	Ballinamore	18
29071	7	L. Cutra	Cutra	36
26020	8	Camiln	Argar Bridge	33
16005	9	Multeen	Aughnagross	35
25029	10	Nenagh	Clarianna	38
24005	11	Morning Star	Athlacca	17
306001	12	Clanrye	Mountmill Bridge	33
19020	13	Owennacurra	Ballyedmond	28
29007	14	L. Cullaun	Craughwell	27
26008	15	Rinn	Johnston's Bridge	55

Flood frequency analysis summary sheet

Station 29007	Dunkellin @ Craughwell

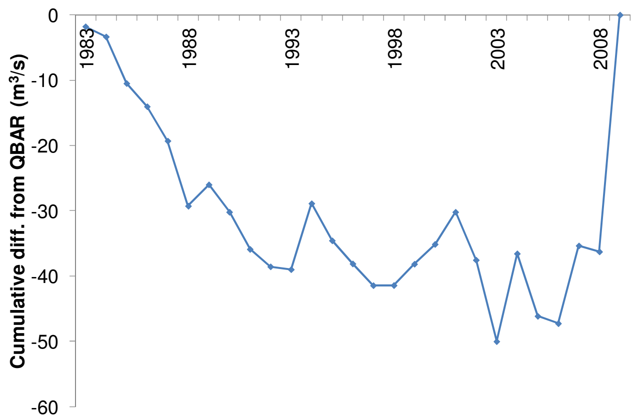


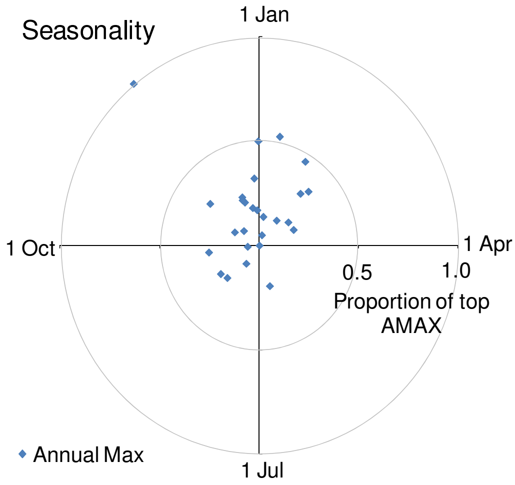
Top ranking floods: QMED (m^3/s): 27.7

Rank	Date	Flow (m^3/s)	AEP (%) from single-site analysis
1	20 November 2009	65.7	0.3
2	09 January 2005	42.9	7.7
3	29 December 2007	41.4	9.3

Tests for stationarity:

Mann-Kendall test: significant increasing trend

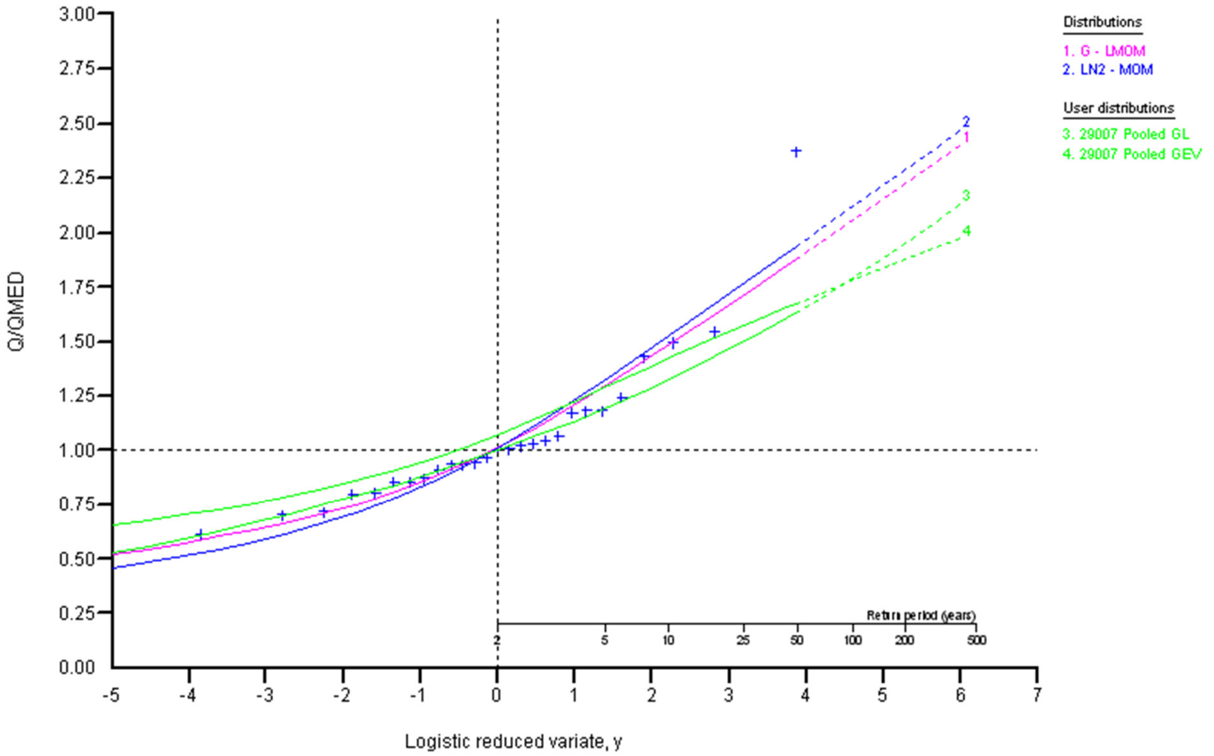




The 27 years of data supplied for this site do not indicate that there is a strong seasonal bias although flood events are possibly least likely to occur between April and July. Generally the AMAX values recorded at this site have not shown a large variation in magnitude with most values being between 20 and 40 m^3/s. However, the 2009 event was much larger ($66m^3/s$). Whilst this was known to be an exceptionally large flood event the possibility that the existing rating over estimated flows in this event should also be considered. This however is unlikely given the small scatter in the check gaugings and the high likelihood of extrapolated lower gaugings indicating the similar results. There appears to be a significant trend of increasing annual maximum flows within this dataset.

Notes: Annual maxima have been sourced directly from OPW. No rating review was undertaken for this site.

Flood frequency analysis – comparison of single-site and pooled growth curves



Distribution	Location	Scale	Shape	100-year growth factor
Single-site Gumbel (L-moments)	0.922	0.247	n/a	2.057
Single-site LN2 (moments)	0.012	0.318	n/a	2.120
Pooled GL (L-moments)	1.000	0.127	-0.125	1.790
Pooled GEV (L-moments)	1.000	0.200	0.072	1.710

Comments on growth curves

There is little difference between the single-site growth curves. If the analysis had been carried out before November 2009, the single-site curves would have been less steep. The pooled analysis shows much shallower growth curves which probably underestimate the AEP of the November 2009 flood: both pooled curves give an AEP of under 0.2% for this event which, while possible, is not considered to be realistic given what is known of the impacts of the flood, full details of which are provided in Appendix C.

Recommended growth curve

The single-site Gumbel curve is recommended as the preferred growth curve for design flood estimation as it gives a more realistic estimate of the November 2009 flood AEP.

Recommended design flows[1] (Single-site Gumbel)

AEPs	50%	20%	10%	5%	2%	1%	0.5%	0.1%
Flow (m^3/s)	27.7	35.8	40.9	45.8	52.2	57.0	64.8	92.9
Growth factor	1.0	1.3	1.5	1.7	1.9	2.1	2.3	3.4

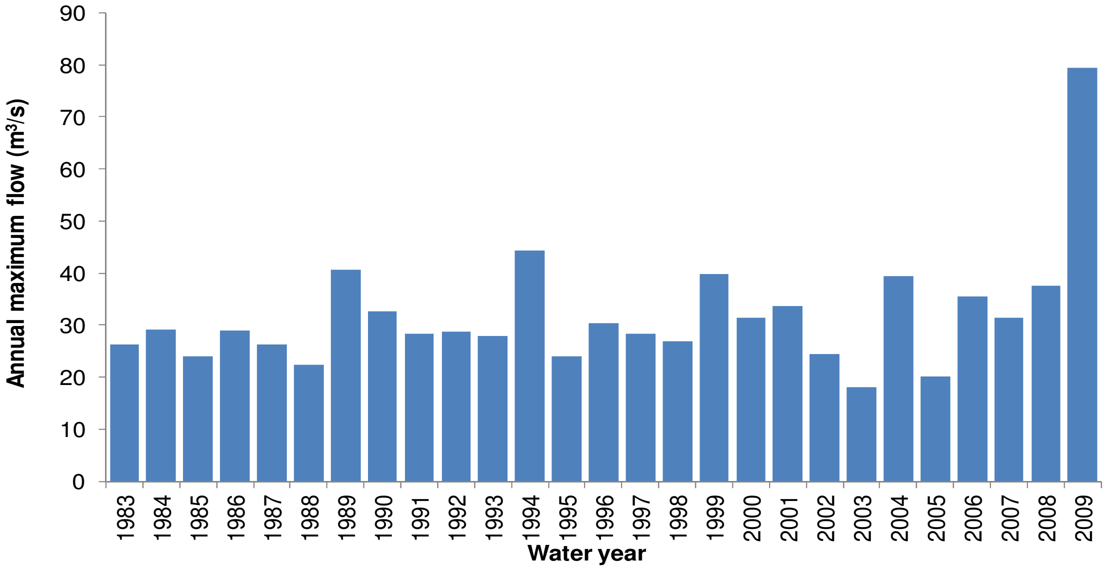
Composition of pooling group

The stations in the pooling group have been selected as the most similar catchments in Ireland and Northern Ireland according to three descriptors at the subject site: AREA (272km^2), SAAR (1094mm) and BFIsoil (0.67).

ID	Rank	Watercourse	Location	Years
29007	1	L. Cullaun	Craughwell	27
29011	2	Dunkellin	Kilcolgan	27
25029	3	Nenagh	Clarianna	38
07004	4	(Kells) Blackwater	Stramatt	24
6011	5	Fane	Moyles Mill	53
30007	6	Clare	Ballygaddy	36
6012	7	Fane	Clarebane	40
06070	8	Muckno L	Muckno	27
36011	9	Erne	Bellahillan	54
26001	10	Shiven	Ballinamore	18
25014	11	Silver	Millbrook Bridge	55
26008	12	Rinn	Johnston's Bridge	55
18004	13	Awbeg	Ballynamona	51

Flood frequency analysis summary sheet

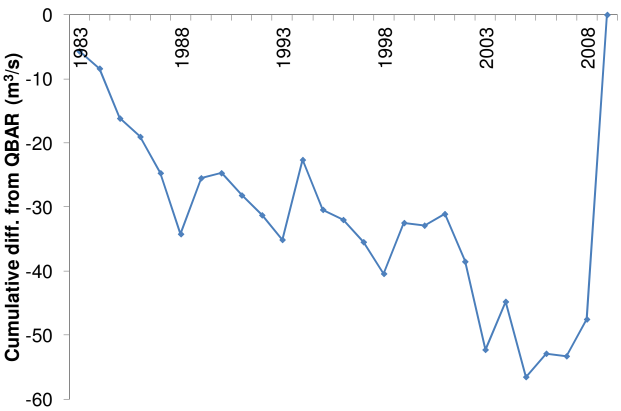
Station 29011	Dunkellin @ Kilcolgan

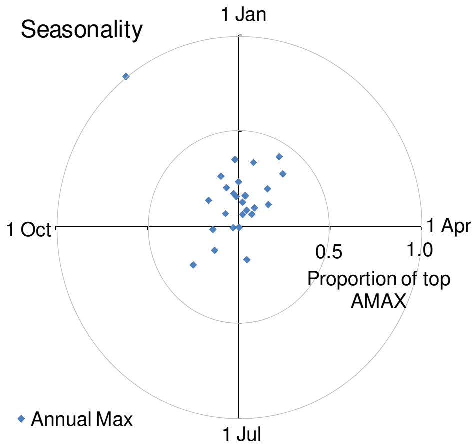


Top ranking floods: QMED (m^3/s): 29.0

Rank	Date	Flow (m^3/s)	AEP (%) from single-site analysis
1	21 November 2009	79.4	0.3
2	30 January 1995	44.3	13.0
3	09 February 1990	40.6	19.0

Tests for stationarity:
Mann-Kendall test: no significant trend

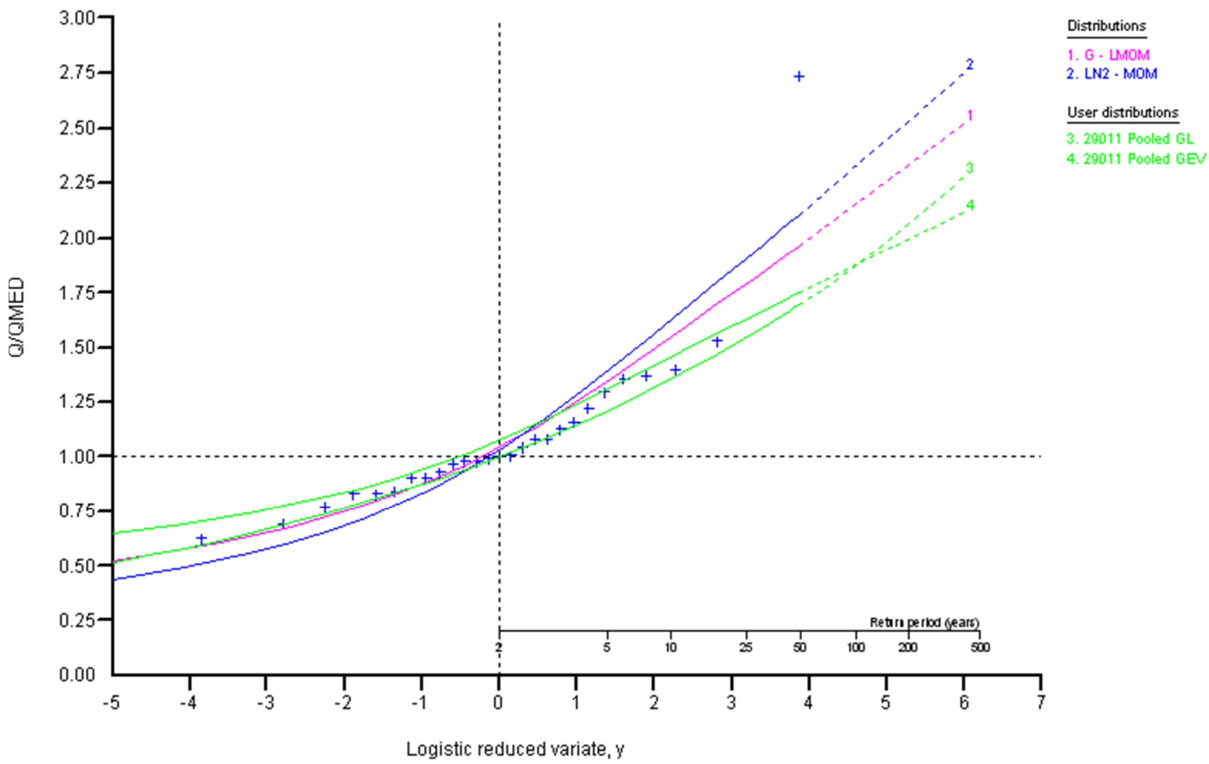




There is a strong seasonal bias in the AMAX data supplied for this site with the majority of events occurring between August and March. In addition there is a large range in the magnitude of AMAX floods, although this is dominated by the exceptionally large flows recorded at the peak of the 2009 event. This event has a growth factor of over 2.7, much higher than the growth factor of 1.5 associated with the second largest flood in the record. There is no significant trend evident within this dataset.

Notes: Annual maxima have been sourced directly from OPW. A rating review was not undertaken for this site.

Flood frequency analysis – comparison of single-site and pooled growth curves



Distribution	Location	Scale	Shape	100-year growth factor
Single-site Gumbel (L-moments)	0.947	0.263	n/a	2.155
Single-site LN2 (moments)	0.034	0.348	n/a	2.235
Pooled GL (L-moments)	1.000	0.135	-0.142	1.880
Pooled GEV (L-moments)	1.000	0.211	0.044	1.800

Comments on growth curves

There is little difference between the single-site growth curves, however, for smaller AEPs; LN2 has a steeper growth curve. The 2009 event is a significant outlier with flows close to twice those of the next highest event observed. This event is having a significant impact on the single-site curves and if the analysis had been carried out before November 2009, the single-site curves would have been less steep. The pooled analysis shows much shallower growth curves and may have overestimated the AEP of the November 2009 flood. Both pooled curves give an AEP of under 0.2% for this event which, while possible, is not considered to be realistic given what is known of the impacts of the flood. The extent of flooding is given in the 2010 report by Tobin and Haskoning and referred to in Appendix C – Flood chronology.

Recommended growth curve

The single-site Gumbel curve is recommended as the preferred growth curve for design flood estimation as it gives a more realistic estimate of the November 2009 flood AEP.

Recommended design flows[1] (Single-site Gumbel)

AEPs	50%	20%	10%	5%	2%	1%	0.5%	0.1%
Flow (m^3/s)	29.0	38.9	44.6	50.1	57.2	62.5	68.9	98.8

Growth factor	1.0	1.3	1.5	1.7	2.0	2.2	2.4	3.4

Composition of pooling group

The stations in the pooling group have been selected as the most similar catchments in Ireland and Northern Ireland according to three descriptors at the subject site: AREA (354km^2), SAAR (1079mm) and BFIsoil (0.63).

ID	Rank	Watercourse	Location	Years
29011	1	Dunkellin	Kilcolgan	27
25029	2	Nenagh	Clarianna	38
30007	3	Clare	Ballygaddy	36
29007	4	L. Cullaun	Craughwell	27
15004	5	Nore	McMahons Bridge	56
26008	6	Rinn	Johnston's Bridge	55
26001	7	Shiven	Ballinamore	18
07004	8	(Kells) Blackwater	Stramatt	24
16010	9	Anner	Anner	56
14005	10	Barrow	Portarlington	53
18004	11	Awbeg	Ballynamona	51
36011	12	Erne	Bellahillan	54
26002	13	Suck	Rookwood	58

C Historical flood chronology

Flood chronology

This appendix provides results from analysis of flood history. Historic flood records were collected from sources such as local newspapers, previous studies, OPW's National Flood Hazard Mapping website, publications on flood history and other relevant websites. Dates and magnitude of more recent events were obtained from hydrometric records. The information was reviewed in order to provide qualitative and, where possible, also quantitative information on the longer-term flood history in the area. Further details relating to the specific flood history of individual AFAs are provided in the relevant Flood Risk Review Reports[1].

The table below gives a chronology of flood events, including information on their impacts.

Date	Catchment/ river	Details
1924	Gort	Major flooding of farm land in Gort/Ardrahan area (mentioned in 1992 GSI report on flooding in the Gort/Ardrahan area[2])
21 June 1930	Kilcolgan	Pluvial flooding in Loughrea, causing 5 inches of water on streets.
Dec 1959	Kilcolgan / Gort	Major flooding of farm land in Gort/Ardrahan area (mentioned in 1992 GSI report on flooding in the Gort/Ardrahan area). Flooding causing 11 inches of water on the road from Craughwell to Gort.
Early 1990	Gort	Winter flooding in Gort/Ardrahan area, south Galway. Large areas of land inundated for several weeks. Roads blocked, schools closed, at least 5 houses flooded. This and subsequent events in the Gort area were primarily groundwater flooding, originating from turloughs. The events have been included in this chronology for the sake of completeness, but full details have not been provided as the CFRAM study is not focused on groundwater flooding.
Jan 1991	Gort	More minor winter flooding in Gort/Ardrahan area.
Early 1994	Gort	Flooding in Gort/Ardrahan area. Apart from the area around Termon, lower levels than 1990 but longer duration. Two houses flooded in the Termon area.
Early 1995	Gort	Extensive winter flooding in Gort/Ardrahan area, primarily groundwater but also fluvial flooding in Gort, particularly in the vicinity of Gort Bridge.
Jan 2005	Kilcolgan	The 2010 report by Tobin and Haskoning[3] started that Jan 2005 was the largest flood before Dec 2009. The report includes aerial photos of flood extents at Craughwell and Rahasane Turlough.

[1] JBA Consulting (2012), Western CFRAM Flood Risk Review, Final Report, Office of Public Works.

[2] Donal Daly (1992), A report on the flooding in the Gort-Ardrahan area, Geological Survey of Ireland.

Date	Catchment/ river	Details
Jan 2005	Athenry	Flooding on the River Clarin, near Athenry reported by Galway County Council.
Nov 2009	Athenry	The 2010 report by Tobin and Haskoning includes photos and a flood extent map. Flooding affected the R349 (Loughrea to Athenry Road) at approximately midday on Thursday 20th November, and then the N6 was closed due to flooding later that afternoon.
Nov 2009	Kilcolgan	The 2010 report by Tobin and Haskoning includes photos and a flood extent map. Flooding affected the R349 (Loughrea to Athenry Road) at approximately midday on Thursday 20th November, and then the N6 was closed due to flooding later that afternoon.
Nov 2009	Gort	Detailed information on the impacts of the Nov 2009 flood in Gort is provided in the Flood Risk Review report, based on information from a report by the EPA, photographs and a site visit. The flooding at Gort was as a result of the highest Lough Cutra water levels since records began, resulting in record outflow; this was combined with rising groundwater levels. The majority of the flooding was downstream of Gort Bridge, thanks to remedial work carried out by OPW in the vicinity of the bridge after the 1995 flood. Crowe Street was particularly badly affected, with 10-12 properties flooded (see photo below). Kinicha Road flooded too (2-3 properties with restricted access to others).  Source: http://www.rte.ie/news/2009/1120/flooding_gallery.html
Nov 2009	Loughrea	Houses flooded on Cross Street due to inadequate culvert capacity. Images have been found showing high levels on Lough Rea flooding the adjacent roads and lake side properties.
Nov 2009	Elsewhere	In November 2009 flooding also affected many other locations,

[3] Tobin Consulting Engineers (2010), Study to identify practical measures to address flooding on the Dunkellin River including the Aggard Stream, Office of Public Works.

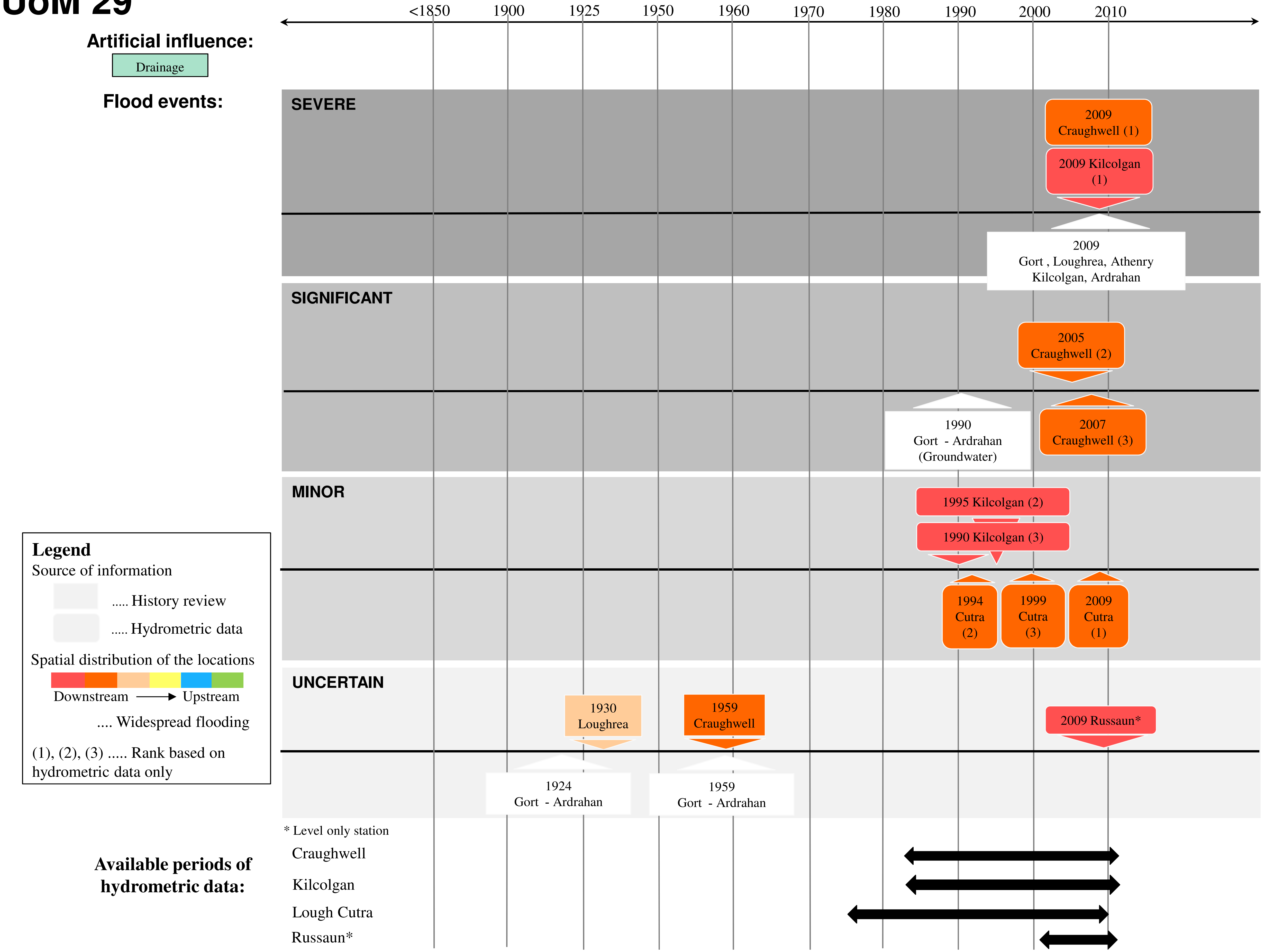
Date	Catchment/ river	Details
		including Ardrahan (fields and roads flooded from groundwater).

Based on the outcomes of the analysis, a flood history time line was produced. The time line provides an overview of the main flooding events by putting together key events extracted from the available hydrometric data (usually limited to the top three events indicated by rank 1-3), and the events indentified in the collated information on historic flooding. The time line sheet also includes locations of the flood events and indicates spatial distribution of these locations (i.e. downstream or upstream along a watercourse).

Four levels of flood severity are used in the table, namely “Severe”, “Significant”, “Minor” and “Unknown” classifications. These are indicative only and are based on the available quantitative and qualitative flood history information. The table below provides details of the classification.

Flood severity classification	AEP (from available data)	Flood severity from historic information
Severe	< 4%	Greatest flood in more than 25 years and/or widespread flooding covering area
Significant	4% - 10%	Widespread flooding
Minor	> 10%	Other
Uncertain	N/A	Other

UoM 29



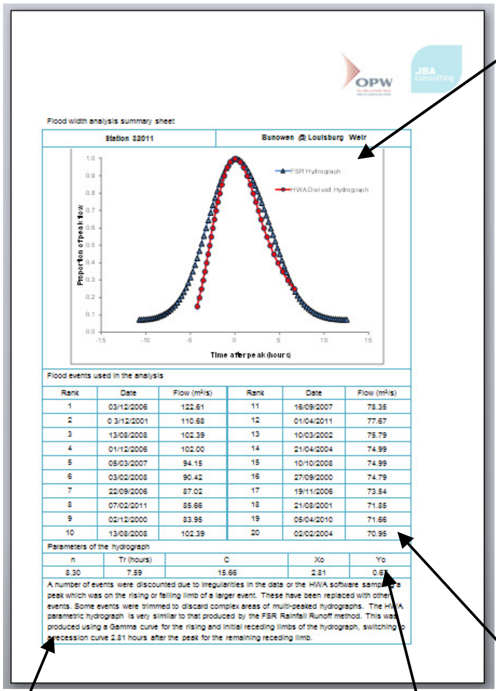
Artificial influence:
Drainage
Flood events:
<1850
1900
1925
1950
1960
1970
1980
1990
2000
2010
SEVERE
2009 Craughwell (1)
2009 Kilcolgan (1)
2009 Gort , Loughrea, Athenry Kilcolgan, Ardrahan
SIGNIFICANT
2005 Craughwell (2)
1990 Gort - Ardrahan (Groundwater)
2007 Craughwell (3)
MINOR
1995 Kilcolgan (2)
1990 Kilcolgan (3)
1994 Cutra (2)
1999 Cutra (3)
2009 Cutra (1)
UNCERTAIN
1930 Loughrea
1959 Craughwell
2009 Russaun*
1924 Gort - Ardrahan
1959 Gort - Ardrahan
* Level only station
Available periods of hydrometric data:
Craughwell
Kilcolgan
Lough Cutra
Russaun*
Legend
Source of information
..... History review
..... Hydrometric data
Spatial distribution of the locations
Downstream → Upstream
.... Widespread flooding
(1), (2), (3) ..... Rank based on hydrometric data only

D Hydrograph width analysis

Introduction to Flood width analysis summary sheets

This appendix summarises the analysis of the widths of observed flood hydrographs. The results of this will be used in the next stage of the study to derive design flood hydrographs.

Information provided in the summary sheets



Flood width analysis summary sheet

Station 32011	Bunowen @ Louisburg Weir

Flood events used in the analysis

Rank	Date	Flow (m^3/s)	Rank	Date	Flow (m^3/s)
1	03/12/2006	122.61	11	16/09/2007	78.35
2	0 3/12/2001	110.68	12	01/04/2011	77.67
3	13/08/2008	102.39	13	10/03/2002	75.79
4	01/12/2006	102.00	14	21/04/2004	74.99
5	05/03/2007	94.15	15	10/10/2008	74.99
6	03/02/2008	90.42	16	27/09/2000	74.79
7	22/09/2006	87.02	17	19/11/2006	73.54
8	07/02/2011	85.66	18	21/08/2001	71.85
9	02/12/2000	83.95	19	05/04/2010	71.66
10	13/08/2008	102.39	20	02/02/2004	70.95

Parameters of the hydrograph

n	Tr (hours)	C	Xo	Yo
8.30	7.59	15.66	2.81	0.6[illegible]

A number of events were discounted due to irregularities in the data or the HWA software samp[illegible] a peak which was on the rising or falling limb of a larger event. These have been replaced with other events. Some events were trimmed to discard complex areas of multi-peaked hydrographs. The HWA parametric hydrograph is very similar to that produced by the FSR Rainfall Runoff method. This was produced using a Gamma curve for the rising and initial receding limbs of the hydrograph, switching [illegible] a recession curve 2.81 hours after the peak for the remaining receding limb.

Flood hydrograph plot

The plot shows characteristic flood hydrographs, i.e. hydrographs that are standardised to peak at 1.0 and plotted so that the time origin is at the peak.

The "HWA derived hydrograph" is a mathematical function fitted to a set of median hydrograph widths from a large number of observed floods. HWA is Hydrograph Width Analysis, a computer program developed within work package 3.1 of the FSU research.

The "FSR hydrograph" is derived from the Flood Studies Report rainfall-runoff method, with model parameters estimated solely from catchment descriptors.

In comparing the two hydrographs it is important to be aware that the FSR hydrograph has the potential to be adjusted in order to give a better fit with the shape of observed events. This would be accomplished by estimating the time to peak parameter via a lag analysis.

List of flood events

These are the events from which the HWA hydrograph was derived. The events initially selected for analysis were the highest 20 floods on record. This list was then refined to exclude events with missing data or events with multiple peaks which could not easily be separated, and other events were added to maintain a total of 20. As recommended in FSU WP3.1, some events were trimmed to discard complex areas of multi-peaked hydrographs.

These 20 hydrographs were analysed to calculate their width at a range of percentiles of the peak flow. The median width was then calculated at each percentile, thus producing a derived hydrograph shape.

Parameters of the fitted hydrograph

This table lists the parameters of the mathematical function fitted to the derived flood hydrograph. Use of a parametric approach is recommended in FSU WP3.1 for studies with multiple flow estimation points such as CFRAMS. The parameters are:

n: Shape parameter of gamma function

Tr: Translation (location) parameter of gamma function

C: Parameter of the exponential function which is used to describe the recession part of the flood hydrograph

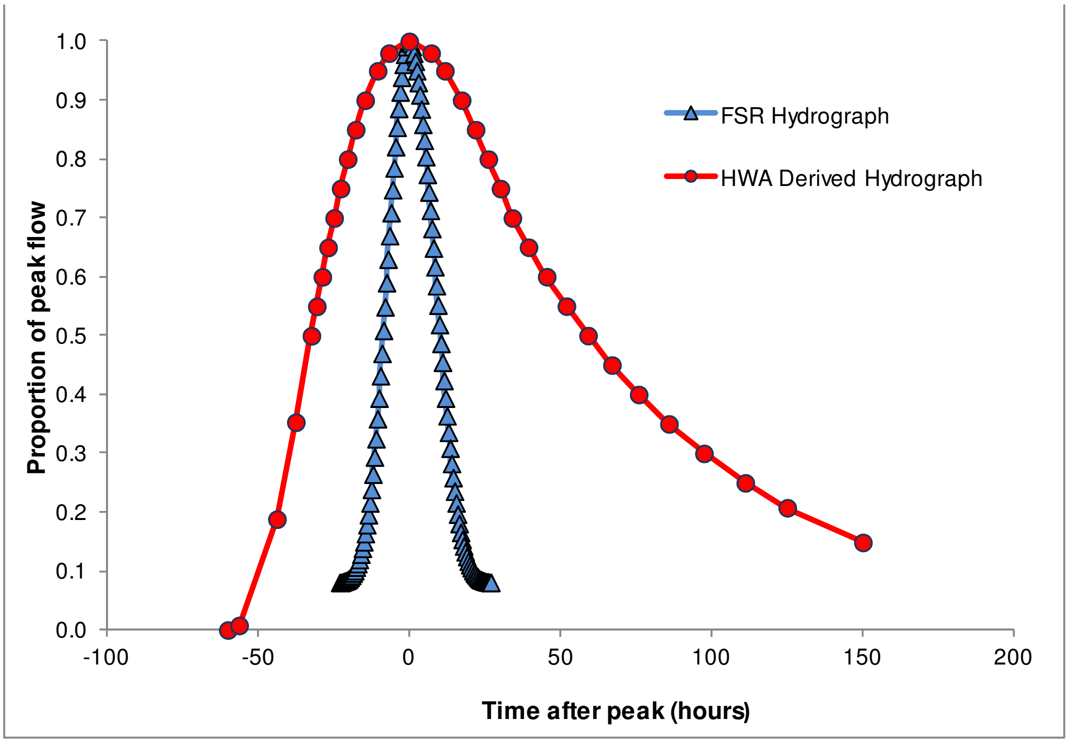
X_0,Y_0: Co-ordinates for the transition between the gamma and exponential functions. X_0 is the time after the peak (in hours) and Y_0 is the normalised flow at this time.

Commentary

Notes on the analysis.

Flood width analysis summary sheet

Station 29001	Raford @ Rathgorgin (116km²)



Flood events used in the analysis

Rank	Date	Flow (m³/s)	Rank	Date	Flow (m³/s)
1	20/11/2009	23.25	11	25/12/1968	16.44
2	29/12/2007	20.37	12	09/09/1974	16.38
3	25/08/2009	18.92	13	27/10/2008	16.17
4	08/10/1964	18.75	14	07/02/1990	15.96
5	10/10/1967	18.42	15	10/11/1977	15.8
6	09/12/2007	18.17	16	10/12/1983	15.72
7	02/12/1973	17.11	17	13/12/1964	15.54
8	01/01/2010	16.99	18	23/01/1975	15.17
9	27/11/2009	16.8	19	01/02/2009	14.73
10	03/12/2007	16.61	20	28/12/1978	14.68

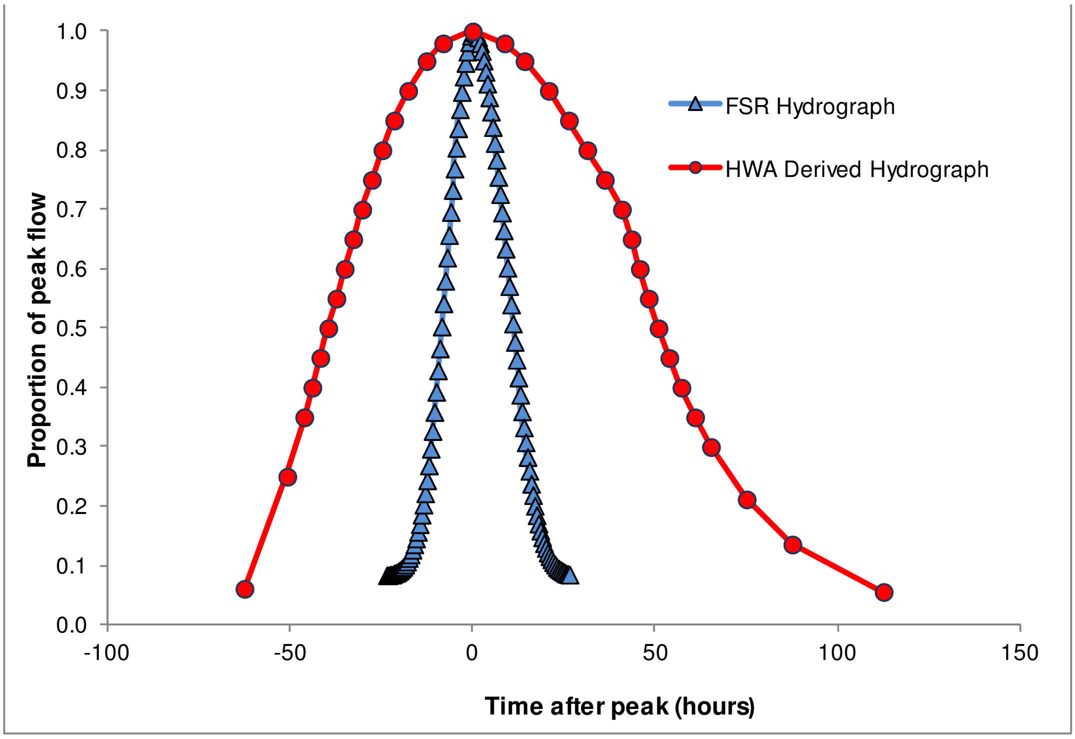
Parameters of the hydrograph

n	Tr (hours)	C	Xo	Yo
4.15	61.58	300.02	34.67	0.69

The 20 largest events on record were sampled at Rathgorgin, with no events removed due to erroneous data or missing periods of record. A number of the sample events were trimmed in order to discard complex areas of multi-peaked hydrographs. The parametric hydrograph produced from the HWA software is significantly wider than that produced by the FSR Rainfall Runoff method. This was produced using a Gamma curve for the rising and initial receding limbs of the hydrograph, switching to a recession curve 34.67 hours after the peak for the remaining receding limb.

Flood width analysis summary sheet

Station 29007	**Dunkellin @ Craughwell (272km^2)**



Flood events used in the analysis

Rank	Date	Flow (m^3/s)	Rank	Date	Flow (m^3/s)
1	20/11/2009	65.74	11	27/11/2009	31.63
2	09/01/2005	42.70	12	05/02/2002	31.12
3	29/12/2007	41.38	13	01/02/1995	30.12
4	08/02/2011	40.39	14	23/09/1999	29.86
5	29/01/1995	39.04	15	14/12/1994	29.35
6	12/02/2002	34.07	16	10/12/1993	29.28
7	10/12/2007	33.20	17	25/08/2009	28.58
8	29/12/1994	33.20	18	22/01/1995	27.97
9	07/11/2000	32.33	19	29/10/1989	27.78
10	08/02/1990	32.23	20	17/01/2011	27.35

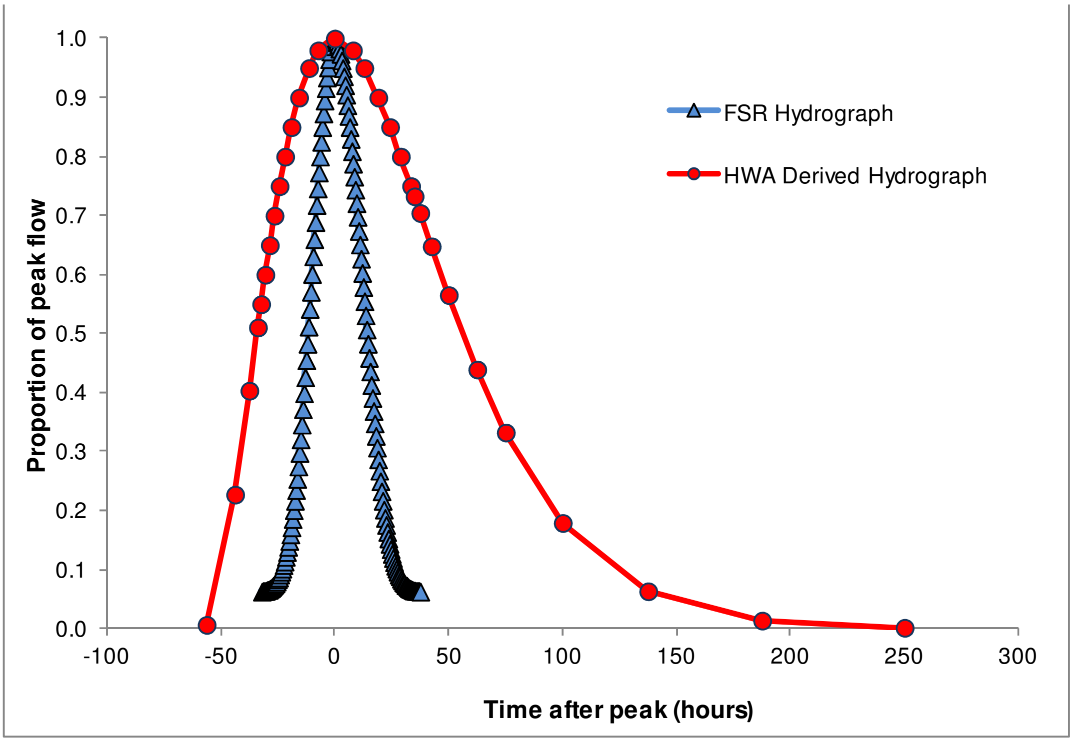
Parameters of the hydrograph

n	Tr (hours)	C	Xo	Yo
4.52	78.50	112.40	41.85	0.69

A number of events were discounted due to irregularities in the data or the HWA software sampling a peak which was on the rising or falling limb of a larger event. These have been replaced with other events and some events were trimmed to discard complex areas of multi-peaked hydrographs. The HWA parametric hydrograph is significantly wider than that produced by the FSR Rainfall Runoff method. This was produced using a Gamma curve for the rising and initial receding limbs of the hydrograph, switching to a recession curve 41.85 hours after the peak for the remaining receding limb.

Flood width analysis summary sheet

Station 30007	Clare @ Ballygaddy (470km²)



Flood events used in the analysis

Rank	Date	Flow (m^3/s)	Rank	Date	Flow (m^3/s)
1	21/11/2009	108.81	11	08/11/1977	69.55
2	30/11/1999	93.38	12	03/12/1992	67.97
3	30/10/1989	92.08	13	27/10/1995	67.34
4	07/02/1990	89.41	14	20/12/1982	66.66
5	05/12/2006	85.11	15	2/01/1991	66.53
6	03/11/1980	80.88	16	11/03/2002	66.08
7	09/01/1992	74.98	17	24/12/1990	66.04
8	07/08/1986	71.09	18	22/1/1995	65.98
9	19/03/1991	70.96	19	27/11/1979	65.92
10	27/05/1985	69.74	20	19/01/1988	64.13

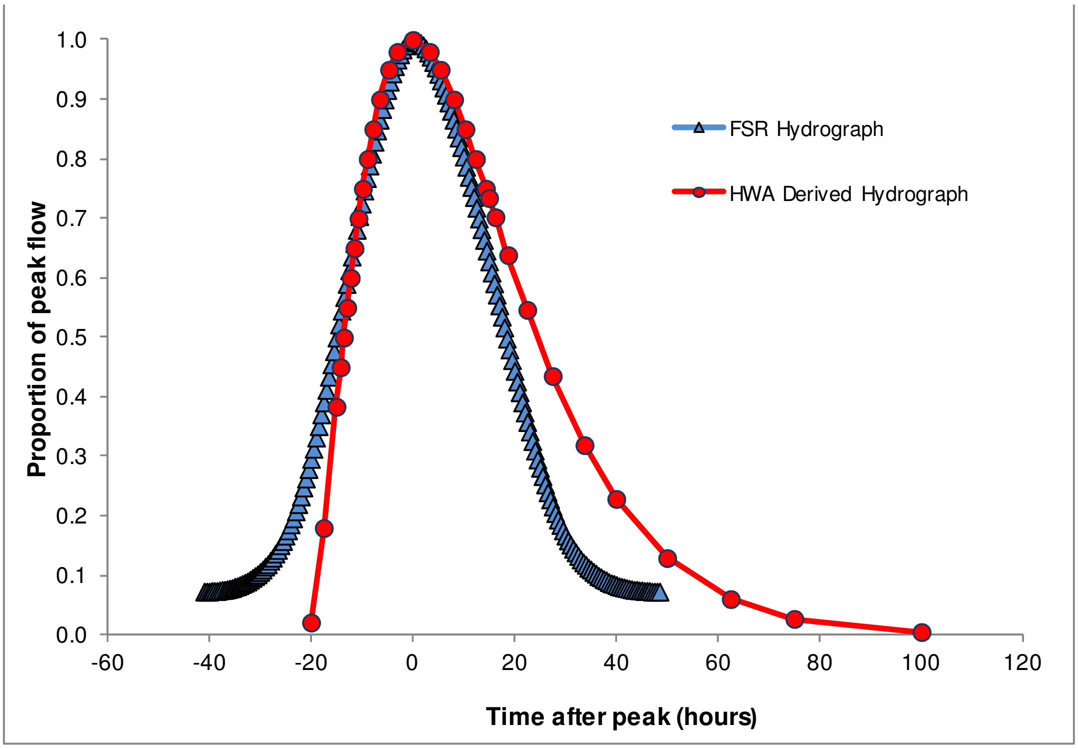
Parameters of the hydrograph

n	Tr (hours)	C	Xo	Yo
3.458	59.25	n/a	n/a	n/a

A number of events were discounted due to irregularities in the data or the HWA software sampling a peak which was on the rising or falling limb of a larger event. These have been replaced with other events and some events were trimmed to discard complex areas of multi-peaked hydrographs. The parametric hydrograph produced from the HWA software is significantly wider than that produced by the FSR Rainfall Runoff method. This was produced using only a Gamma curve (unlike some locations where the falling limb is derived using a Recession curve).

Flood width analysis summary sheet

Station 30012	Clare @ Claregalway (1073km^2)



Flood events used in the analysis

Rank	Date	Flow (m^3/s)	Rank	Date	Flow (m^3/s)
1	22/11/2009	165.26	11	27/10/2008	117.37
2	07/12/2006	136.74	12	12/02/2002	115.46
3	08/02/2011	127.52	13	30/12/2007	112.02
4	18/01/2011	127.15	14	11/03/2002	109.60
5	12/10/2008	125.97	15	18/08/2008	107.26
6	10/01/2005	123.56	16	25/08/2009	104.54
7	07/04/2010	121.75	17	12/01/2007	104.00
8	06/02/2002	121.32	18	14/12/2000	103.87
9	10/12/2007	120.81	19	09/11/2010	103.73
10	6/02/2008	118.80	20	22/01/2008	103.06

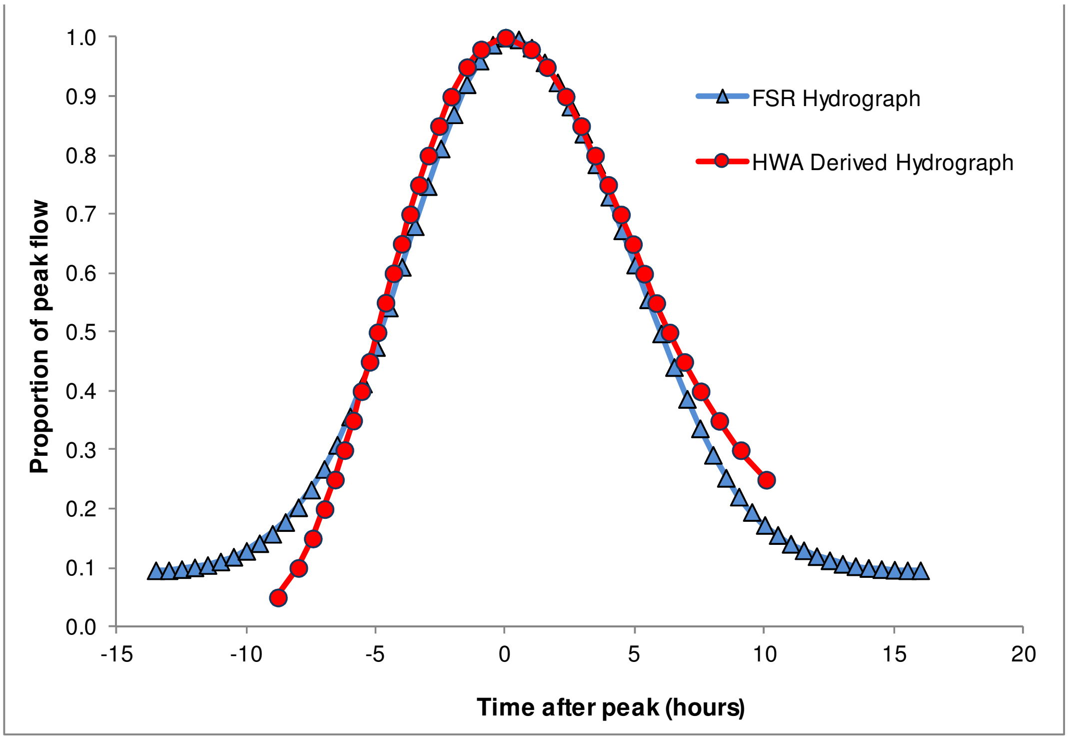
Parameters of the hydrograph

n	Tr (hours)	C	Xo	Yo
2.74	20.88	n/a	n/a	n/a

A number of events were discounted due to irregularities in the data or the HWA software sampling a peak which was on the rising or falling limb of a larger event. These have been replaced with other events and some events were trimmed to discard complex areas of multi-peaked hydrographs. The parametric HWA hydrograph is narrower than that produced by the FSR Rainfall Runoff method, with a slightly swifter time to rise, but a longer falling limb. This was produced using only a Gamma curve (unlike some locations where the falling limb is derived using a Recession curve).

Flood width analysis summary sheet

Station 30019	Owenriff @ Claremount (63km²)



Flood events used in the analysis

Rank	Date	Flow (m^3/s)	Rank	Date	Flow (m^3/s)
1	28/11/1999	204.83	11	14/12/1983	64.16
2	27/10/1989	92.54	12	19/09/1985	64.09
3	27/01/1995	84.78	13	21/10/1998	62.40
4	26/10/1995	76.96	14	12/10/1983	62.39
5	21/10/1988	73.65	15	13/12/1994	61.98
6	18/03/1991	73.37	16	05/12/1986	61.64
7	01/01/1991	67.21	17	07/11/1977	61.04
8	22/12/1991	66.48	18	10/04/1991	59.08
9	10/01/1998	64.86	19	28/11/1996	58.87
10	22/12/1999	64.38	20	31/01/1983	58.07

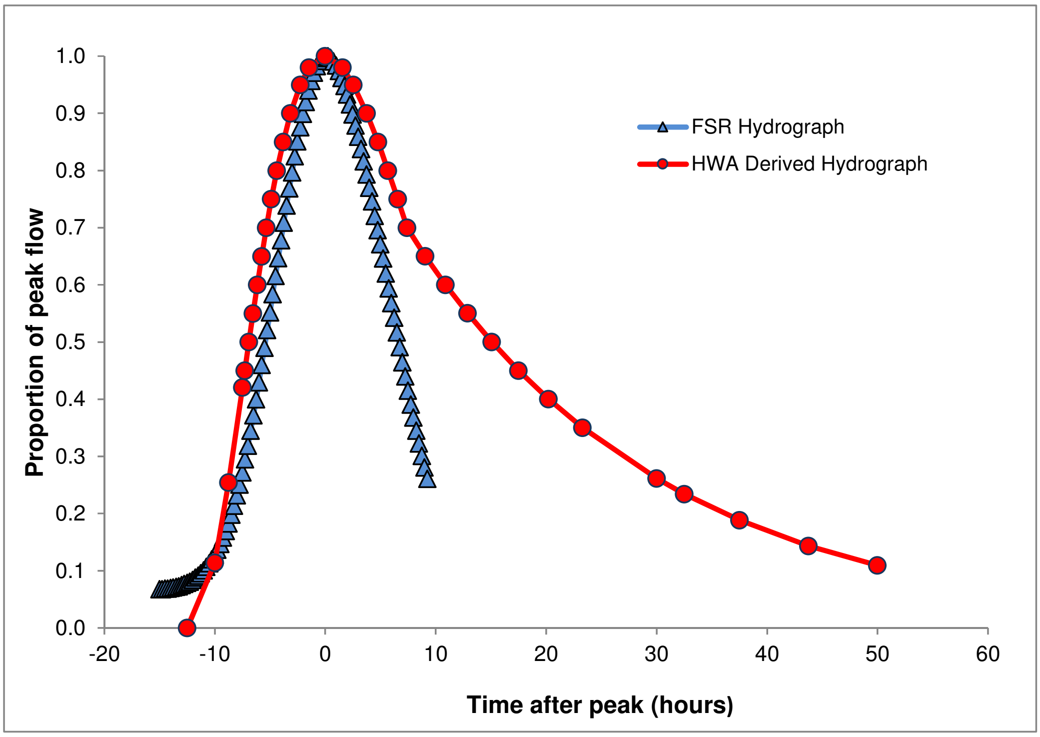
Parameters of the hydrograph

n	Tr (hours)	C	Xo	Yo
9.84	14.29	21.52	4.81	0.66

The 20 largest events on record were sampled at Claremount, with no events removed due to erroneous data or missing periods of record. A number of the sample events were trimmed in order to discard complex areas of multi-peaked hydrographs. The parametric hydrograph produced from the HWA software is very similar to that produced by the FSR Rainfall Runoff method. This was produced using a Gamma curve for the rising and initial receding limbs of the hydrograph, switching to a recession curve 4.81 hours after the peak for the remaining receding limb.

Flood width analysis summary sheet

Station 30020	Clare @ Ballyhaunis (21km²)



Flood events used in the analysis

Rank	Date	Flow (m^3/s)	Rank	Date	Flow (m^3/s)
1	19/11/2009	7.50	11	21/1/2008	4.04
2	06/09/2010	6.20	12	05/03/2007	3.97
3	03/12/2006	5.05	13	18/11/2009	3.94
4	16/11/2009	5.00	14	07/01/2005	3.92
5	01/02/2004	4.69	15	25/05/2005	3.92
6	08/12/2007	4.65	16	26/10/2006	3.87
7	03/12/2001	4.61	17	23/08/2009	3.84
8	10/03/2002	4.39	18	10/10/2008	3.79
9	07/02/2011	4.20	19	21/11/2009	3.66
10	03/02/2008	4.07	20	06/04/2010	3.52

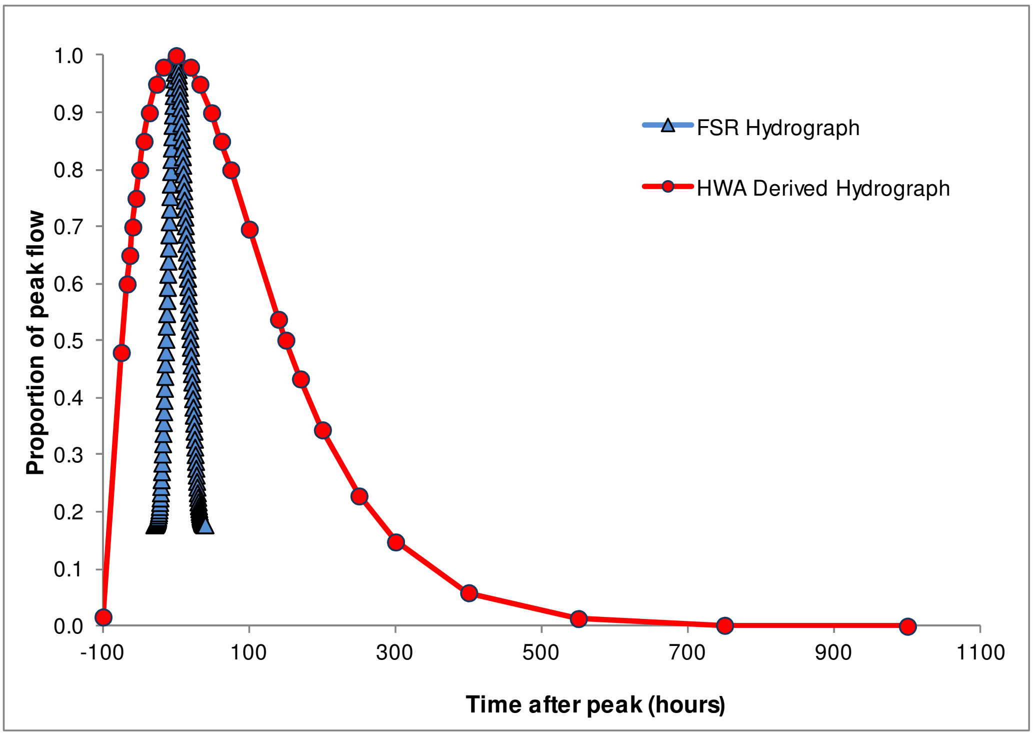
Parameters of the hydrograph

n	Tr (hours)	C	Xo	Yo
3.88	12.74	91.88	7.50	0.70

The 20 largest events on record were sampled at Ballyhaunis, with no events removed due to erroneous data or missing periods of record. Some events were trimmed in order to discard complex areas of multi-peaked hydrographs. The parametric hydrograph produced from the HWA software is narrower than that produced by the FSR Rainfall Runoff method, with a swifter time to rise, but a longer falling limb. This was produced using a Gamma curve for the rising and initial receding limbs, switching to a recession curve 7.50 hours after the peak for the remaining receding limb.

Flood width analysis summary sheet

Station 30061	Corrib @ Galway (Wolfe Tone Bridge) (3136km^2)



Flood events used in the analysis

Rank	Date	Flow (m^3/s)	Rank	Date	Flow (m^3/s)
1	25/01/1975	441.05	11	12/04/1991	284.42
2	29/12/1974	337.33	12	17/01/1984	284.11
3	05/01/1991	332.12	13	07/02/1992	283.24
4	27/02/1990	321.91	14	09/02/1988	282.28
5	09/12/1954	299.33	15	01/02/1995	281.64
6	07/01/1975	297.81	16	09/03/1993	276.83
7	12/11/1977	289.82	17	06/01/1994	275.26
8	18/02/1980	286.87	18	24/01/1993	274.48
9	06/02/1980	286.11	19	01/01/1960	273.56
10	05/11/1989	285.75	20	20/12/1954	272.92

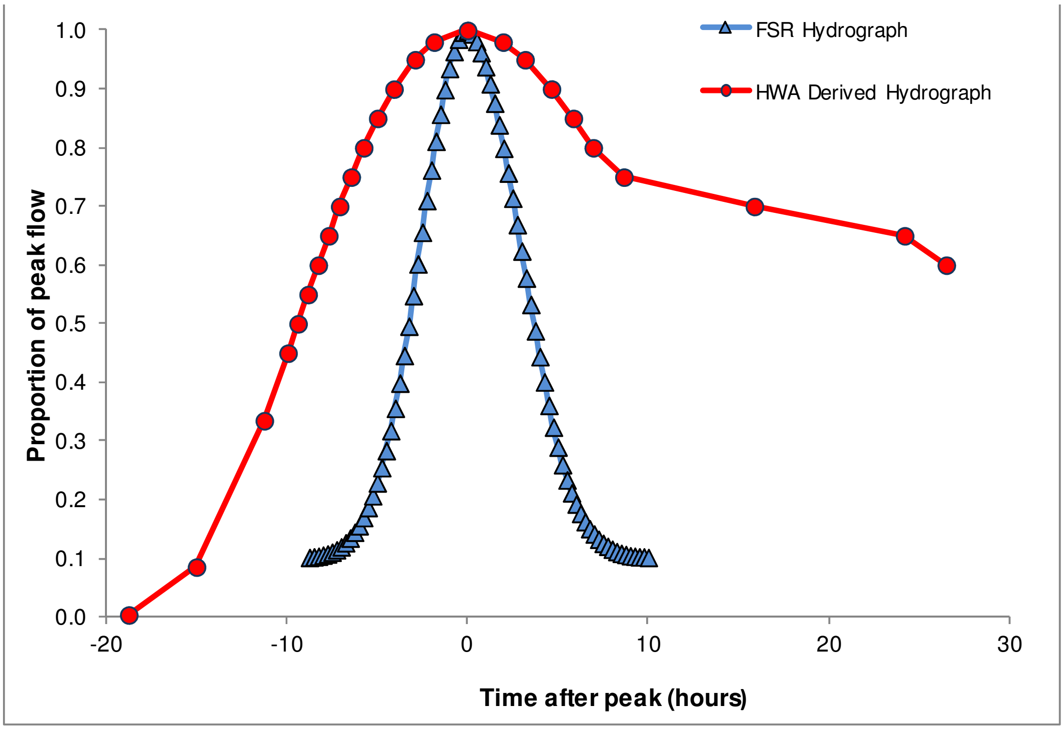
Parameters of the hydrograph

n	Tr (hours)	C	Xo	Yo
2.20	101	n/a	n/a	n/a

A number of events were discounted due to irregularities in the data or the HWA software sampling a peak which was on the rising or falling limb of a larger event. These have been replaced with other events and some events were trimmed to discard complex areas of multi-peaked hydrographs. The parametric HWA hydrograph is significantly wider than that produced by the FSR Rainfall Runoff method, with a much longer falling limb. The extreme difference in widths is unsurprising as the FSR method does not account for the presence of lakes in the catchment.

Flood width analysis summary sheet

Station 32012	Newport @ Newport Weir (146km²)



Flood events used in the analysis

Rank	Date	Flow (m^3/s)	Rank	Date	Flow (m^3/s)
1	03/12/2006	37.60	11	03/07/2009	31.76
2	07/02/2011	36.30	12	08/11/2010	30.58
3	08/12/2007	36.04	13	05/12/2001	30.12
4	04/11/2010	35.72	14	22/12/2004	29.71
5	13/08/2008	35.66	15	11/12/2006	29.60
6	10/10/2008	35.34	16	27/10/2000	29.37
7	15/01/2005	34.02	17	19/02/2002	29.08
8	21/01/2008	33.34	18	08/09/2010	28.62
9	27/10/2002	32.30	19	08/01/2007	28.35
10	20/01/2005	31.88	20	24/02/2002	28.24

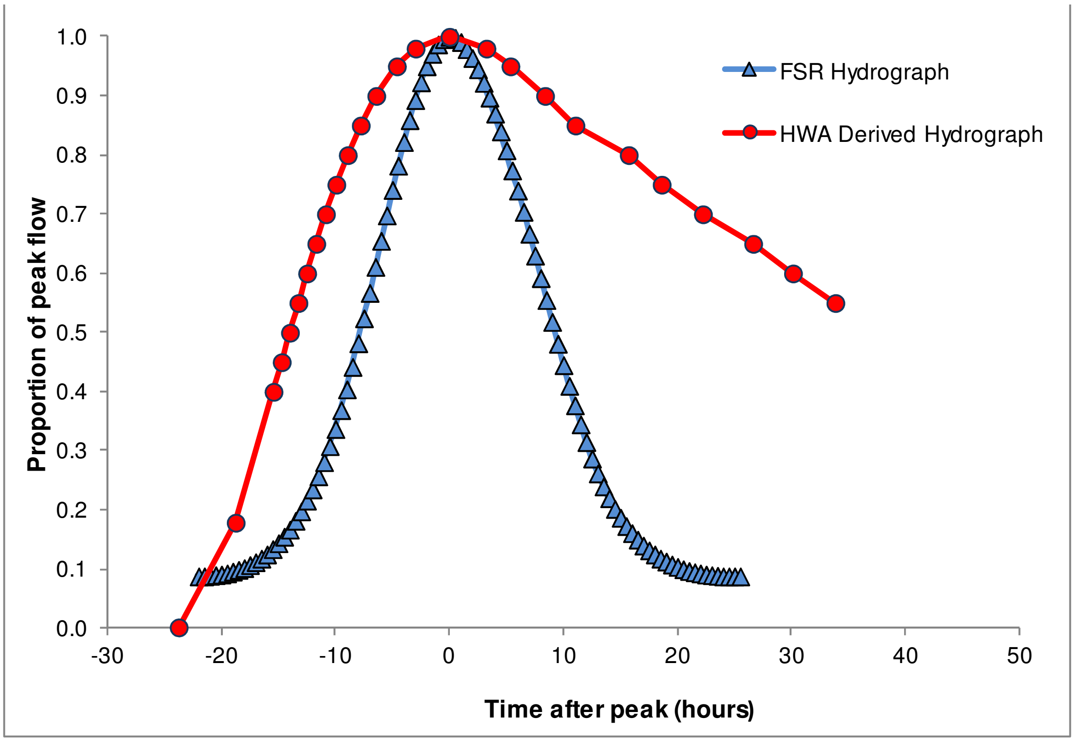
Parameters of the hydrograph

n	Tr (hours)	C	Xo	Yo
6.52	22.28	n/a	n/a	n/a

A number of events were discounted due to irregularities in the data or the HWA software sampling a peak which was on the rising or falling limb of a larger event. These have been replaced with other events. Some events were trimmed to discard complex areas of multi-peaked hydrographs. The HWA parametric hydrograph is wider than that produced by the FSR Rainfall Runoff method. This was produced using a Gamma curve for the rising and initial receding limbs of the hydrograph, switching to the non parametric hydrograph (as both the Gamma and Recession curves offered a poor fit).

Flood width analysis summary sheet

Station 32006	Carrowbeg @ Coolloughra (36km²)



Flood events used in the analysis

Rank	Date	Flow (m³/s)	Rank	Date	Flow (m³/s)
1	19/11/2009	15.54	11	06/03/2007	9.35
2	03/12/2006	13.53	12	30/11/2006	9.26
3	24/11/2009	12.52	13	20/11/2006	9.07
4	16/08/2008	11.89	14	01/11/2009	8.59
5	14/12/2006	10.45	15	04/11/2009	8.50
6	22/11/2009	10.20	16	02/12/2007	8.20
7	09/12/2007	10.12	17	18/01/2009	7.82
8	25/10/2008	10.10	18	07/11/2009	7.76
9	14/08/2008	10.07	19	23/10/2008	7.66
10	03/02/2008	9.86	20	03/11/2005	7.65

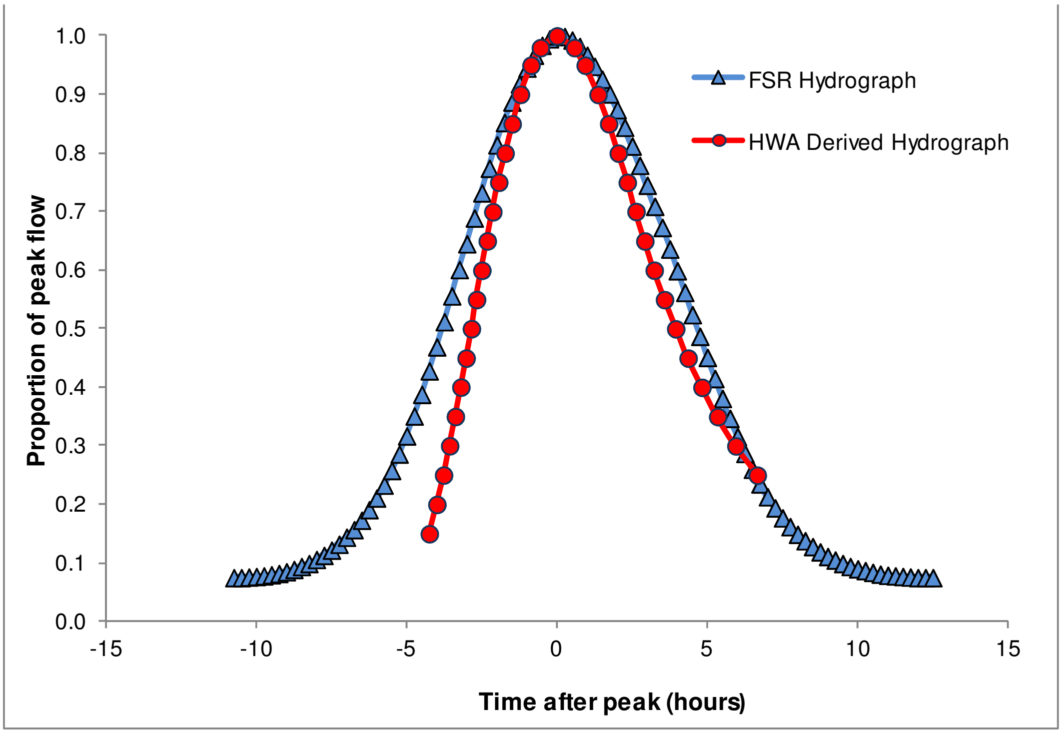
Parameters of the hydrograph

n	Tr (hours)	C	Xo	Yo
3.52	98.02	n/a	n/a	n/a

A number of events were discounted due to irregularities in the data or the HWA software sampling a peak which was on the rising or falling limb of a larger event. These have been replaced with other events. Some events were trimmed to discard complex areas of multi-peaked hydrographs. The HWA parametric hydrograph is wider than that produced by the FSR Rainfall Runoff method. This was produced using a Gamma curve for the rising and initial receding limbs of the hydrograph, switching to the non parametric hydrograph (as both the Gamma and Recession curves offered a poor fit).

Flood width analysis summary sheet

Station 32011	Bunowen @ Louisburg Weir (70km²)



Flood events used in the analysis

Rank	Date	Flow (m^3/s)	Rank	Date	Flow (m^3/s)
1	03/12/2006	122.61	11	16/09/2007	78.35
2	0 3/12/2001	110.68	12	01/04/2011	77.67
3	13/08/2008	102.39	13	10/03/2002	75.79
4	01/12/2006	102.00	14	21/04/2004	74.99
5	05/03/2007	94.15	15	10/10/2008	74.99
6	03/02/2008	90.42	16	27/09/2000	74.79
7	22/09/2006	87.02	17	19/11/2006	73.54
8	07/02/2011	85.66	18	21/08/2001	71.85
9	02/12/2000	83.95	19	05/04/2010	71.66
10	13/08/2008	102.39	20	02/02/2004	70.95

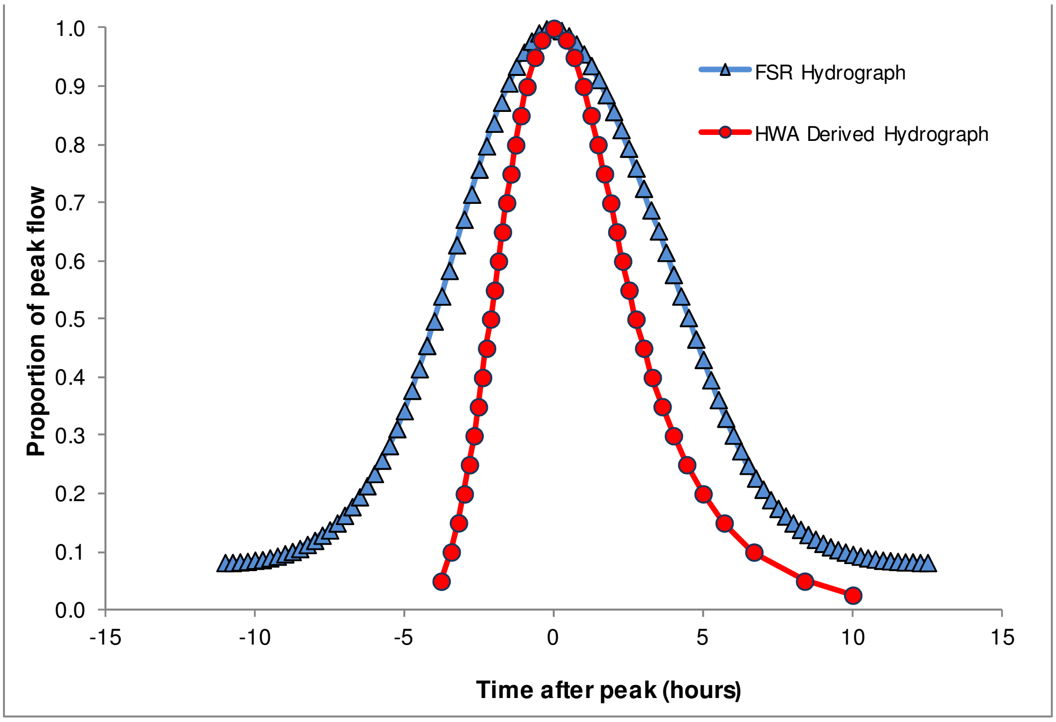
Parameters of the hydrograph

n	Tr (hours)	C	Xo	Yo
8.30	7.59	15.66	2.81	0.67

A number of events were discounted due to irregularities in the data or the HWA software sampling a peak which was on the rising or falling limb of a larger event. These have been replaced with other events. Some events were trimmed to discard complex areas of multi-peaked hydrographs. The HWA parametric hydrograph is very similar to that produced by the FSR Rainfall Runoff method. This was produced using a Gamma curve for the rising and initial receding limbs of the hydrograph, switching to a recession curve 2.81 hours after the peak for the remaining receding limb.

Flood width analysis summary sheet

Station 32004	Owenglin @ Clifden (32km²)



Flood events used in the analysis

Rank	Date	Flow (m^3/s)	Rank	Date	Flow (m^3/s)
1	21/9/2006	56.00	11	10/10/2008	36.00
2	16/8/2008	49.20	12	26/2/2007	35.70
3	13/8/2008	47.10	13	10/12/2004	35.50
4	19/8/2009	44.90	14	7/9/2010	33.60
5	5/10/2006	41.60	15	21/5/2003	33.50
6	25/5/2005	40.50	16	11/11/2010	33.20
7	3/12/2006	38.60	17	22/6/2008	33.10
8	4/11/2010	38.00	18	30/11/2006	32.70
9	23/8/2004	37.90	19	20/6/2007	32.50
10	23/8/2009	36.20	20	18/1/2007	32.30

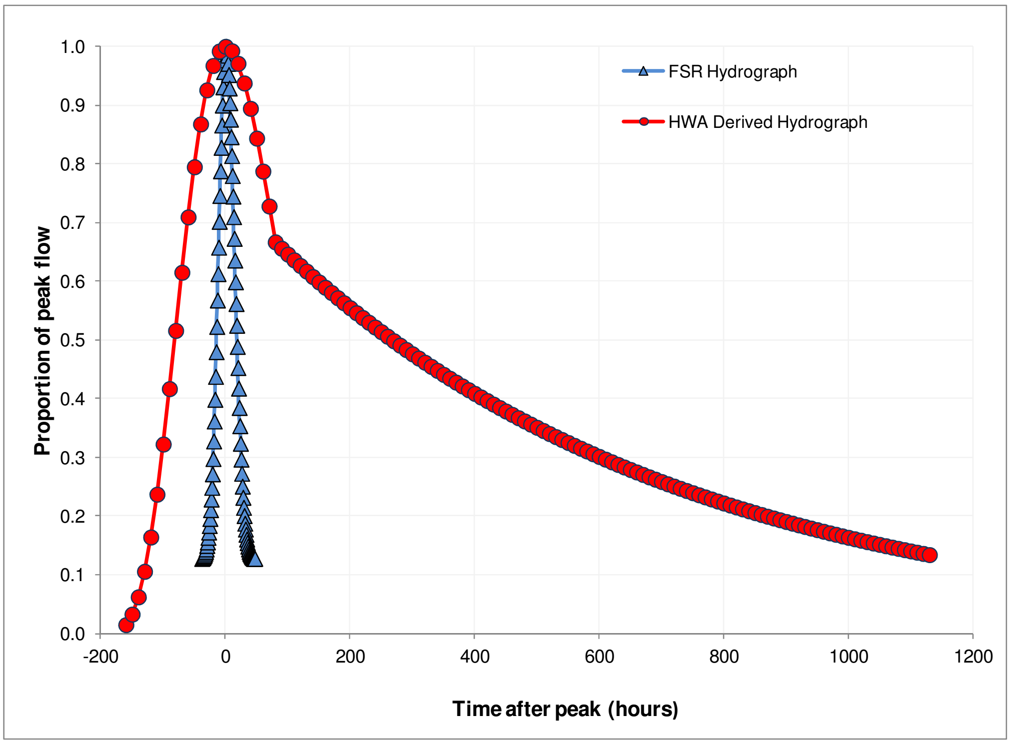
Parameters of the hydrograph

n	Tr (hours)	C	Xo	Yo
10.00	6.17	9.80	2.06	0.66

No events were removed due to erroneous data or missing periods of record. Some events were trimmed to discard complex areas of multi-peaked hydrographs. The HWA parametric hydrograph is narrower than that produced by the FSR Rainfall Runoff method. This was produced using a Gamma curve for the rising and initial receding limbs of the hydrograph, switching to a recession curve 2.06 hours after the peak for the remaining receding limb.

Flood width analysis summary sheet

Station 34001	Moy @ Rahans (1974km^2)



Flood events used in the analysis

Rank	Date	Flow (m^3/s)	Rank	Date	Flow (m^3/s)
1	30/ 10/ 1989	288.34	6	10/ 1/ 1998	214.7
2	26/ 11/ 2009	230.71	7	3/ 11/ 1980	207.4
3	7/ 2/ 1990	228.37	8	2/ 2/ 1984	197.88
4	6/ 1/ 1991	223.18	9	24/ 1/ 1993	191.34
5	15/ 12/ 2006	215.96	10	10/ 12/ 2007	188.9

Parameters of the hydrograph

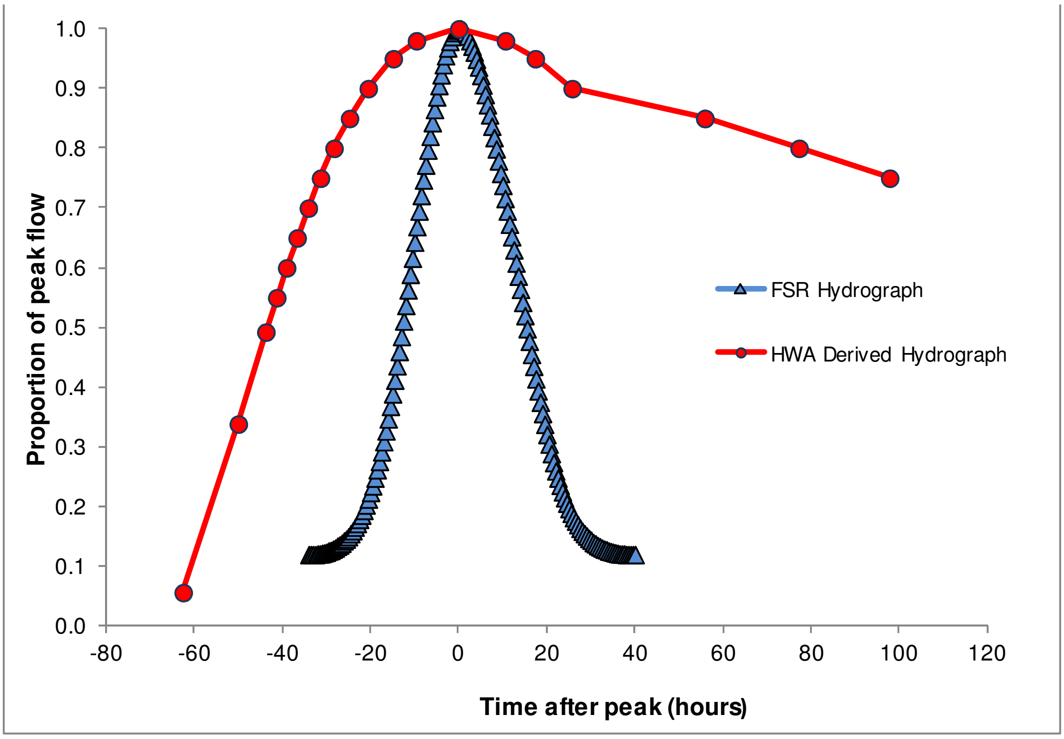
n	Tr (hours)	C	Xo	Yo
8.89	225	656	80.1	0.67

Analysis at this station was added after completion of the inception phase, when it became apparent that design hydrograph shapes for input to the HPW model at Ballina would be best represented using observed hydrograph shapes.

Hydrographs on the River Moy are extremely prolonged, with the river staying high typically for months during a winter flood. The time window for analysis using HWA was set to 600 hours before the peak and 1600 hours after the peak, i.e. a total time span of 3 months. Many events were excluded because there was no clearly defined hydrograph. Ten events were included in the final analysis.

HWA results for this station are included in the report on FSU WP 3.4. The derived median hydrograph is very different to that shown above. It appears that the analysis in WP 3.4 did not identify more than the top portion of most hydrographs, probably due to specifying a too-narrow time window. The results above are more convincing, giving a median hydrograph very much wider than that from the FSR rainfall-runoff method (applied using catchment descriptors), which does not account for the presence of large volumes of storage in the upstream catchment, in particular Loughs Conn and Cullin.

Station 34003	Moy @ Foxford (1805km^2)



Flood events used in the analysis

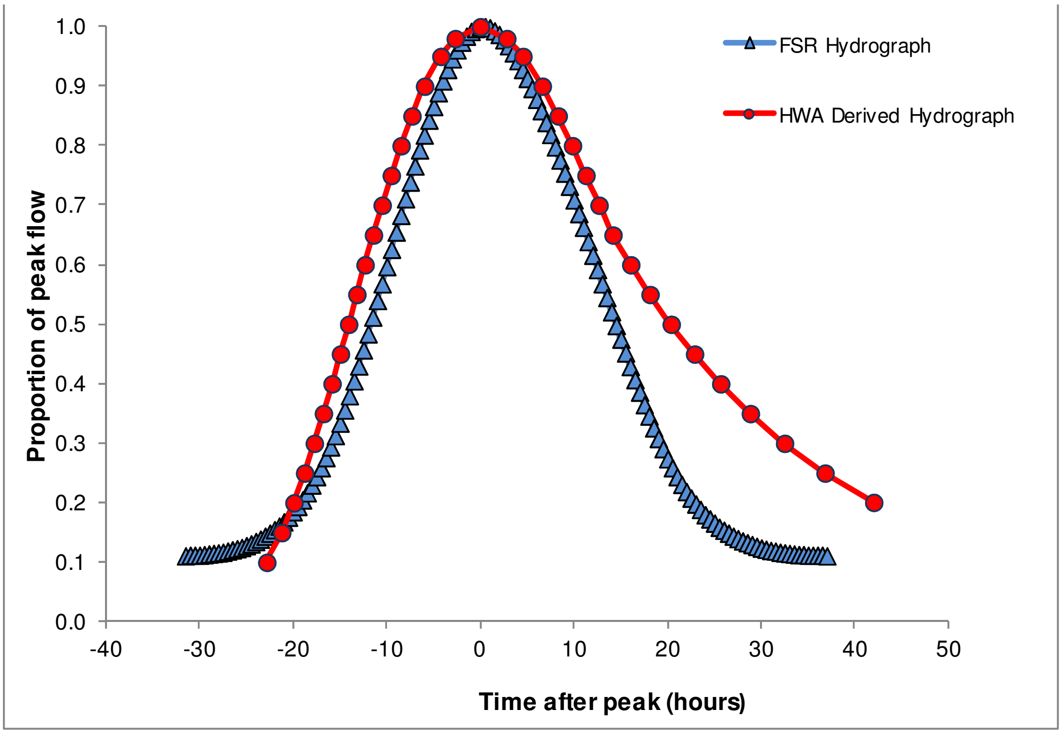
Rank	Date	Flow (m^3/s)	Rank	Date	Flow (m^3/s)
1	24/11/2009	259.23	11	17/11/2009	179.40
2	14/12/2006	243.00	12	11/01/2007	174.64
3	20/11/2009	231.33	13	07/02/2011	174.64
4	11/12/2006	223.43	14	16/01/2005	171.83
5	10/12/2007	195.01	15	07/12/2009	171.83
6	02/12/2009	189.89	16	18/01/2007	171.69
7	04/12/2006	189.59	17	20/02/2002	168.91
8	10/01/2005	184.08	18	13/12/2000	163.13
9	11/02/2002	182.41	19	04/12/2000	159.00
10	21/01/2005	179.40	20	21/01/2008	155.35

Parameters of the hydrograph

n	Tr (hours)	C	Xo	Yo
2.85	68.27	n/a	n/a	n/a

A number of events were discounted due to irregularities in the data or the HWA software sampling a peak which was on the rising or falling limb of a larger event. These have been replaced with other events. Some events were trimmed to discard complex areas of multi-peaked hydrographs. The HWA parametric hydrograph is wider than that produced by the FSR Rainfall Runoff method. This was produced using a Gamma curve for the rising and initial receding limbs of the hydrograph, switching to the non parametric hydrograph (as both the Gamma and Recession curves offered a poor fit).

Station 34004	Moy @ Ballylahan (935km²)



Flood events used in the analysis

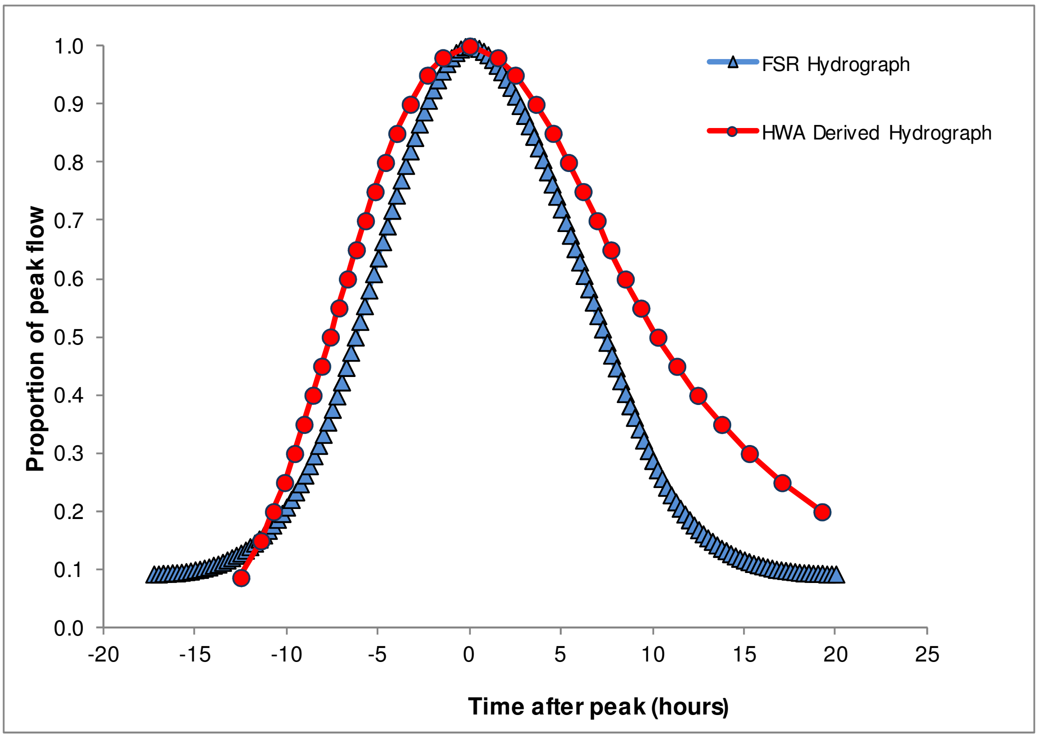
Rank	Date	Flow (m³/s)	Rank	Date	Flow (m³/s)
1	28/10/1989	374.50	11	27/05/1985	252.59
2	02/11/1980	331.08	12	15/01/1975	248.95
3	10/01/1998	308.04	13	21/10/1998	246.90
4	28/11/1999	299.89	14	14/12/1983	243.97
5	26/11/1979	291.78	15	21/12/1985	243.83
6	15/11/1978	283.29	16	19/12/1982	241.08
7	05/12/1986	278.59	17	08/01/2005	239.41
8	14/08/2008	263.9	18	26/10/1995	233.18
9	05/11/1999	258.67	19	21/09/1985	231.54
10	06/08/1986	253.87	20	08/01/1992	230.95

Parameters of the hydrograph

n	Tr (hours)	C	Xo	Yo
10.00	41.05	94.81	13.68	0.66

A number of events were discounted due to irregularities in the data or the HWA software sampling a peak which was on the rising or falling limb of a larger event. These have been replaced with other events. Some events were trimmed to discard complex areas of multi-peaked hydrographs. The HWA parametric hydrograph is similar to that produced by the FSR Rainfall Runoff method, although the receding limb is a little longer. This was produced using a Gamma curve for the rising and initial receding limbs of the hydrograph, switching to a recession curve 13.68 hours after the peak.

Station 34007	Deel @ Ballycarroon (152km²)



Flood events used in the analysis

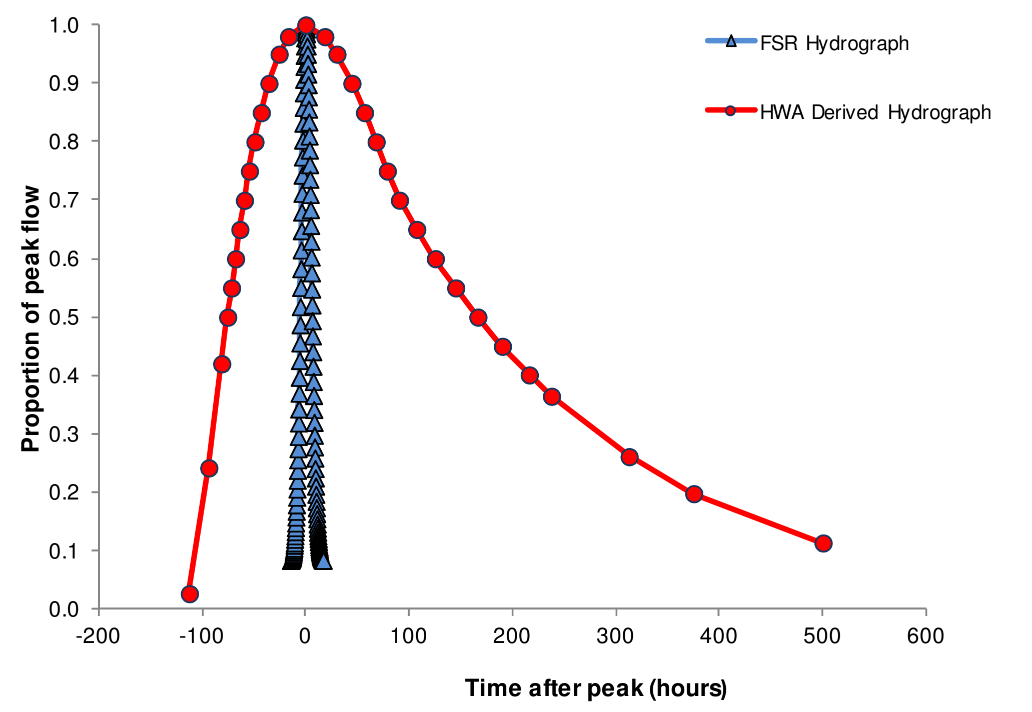
Rank	Date	Flow (m^3/s)	Rank	Date	Flow (m^3/s)
1	28/10/1989	159.84	11	02/11/1980	104.11
2	27/11/1979	144.07	12	21/10/1998	97.46
3	01/10/1985	143.29	13	19/12/1982	97.04
4	03/12/2006	133.93	14	03/12/2001	96.28
5	05/12/1986	132.91	15	14/01/1988	95.70
6	07/09/1980	122.90	16	01/11/1986	95.39
7	15/11/1978	118.32	17	27/10/2002	91.72
8	28/09/1978	116.42	18	06/08/1986	89.90
9	11/09/1992	108.61	19	16/11/1986	89.54
10	01/01/1998	105.93	20	18/10/1984	89.35

Parameters of the hydrograph

n	Tr (hours)	C	Xo	Yo
8.89	20.98	39.11	7.47	0.67

A number of events were discounted due to irregularities in the data or the HWA software sampling a peak which was on the rising or falling limb of a larger event. These have been replaced with other events. Some events were trimmed to discard complex areas of multi-peaked hydrographs. The HWA parametric hydrograph is similar to that produced by the FSR Rainfall Runoff method, although the receding limb is a little longer. This was produced using a Gamma curve for the rising and initial receding limbs of the hydrograph, switching to a recession curve 7.47 hours after the peak.

Station 34018	Castlebar @ Turlough (95km²)



Flood events used in the analysis

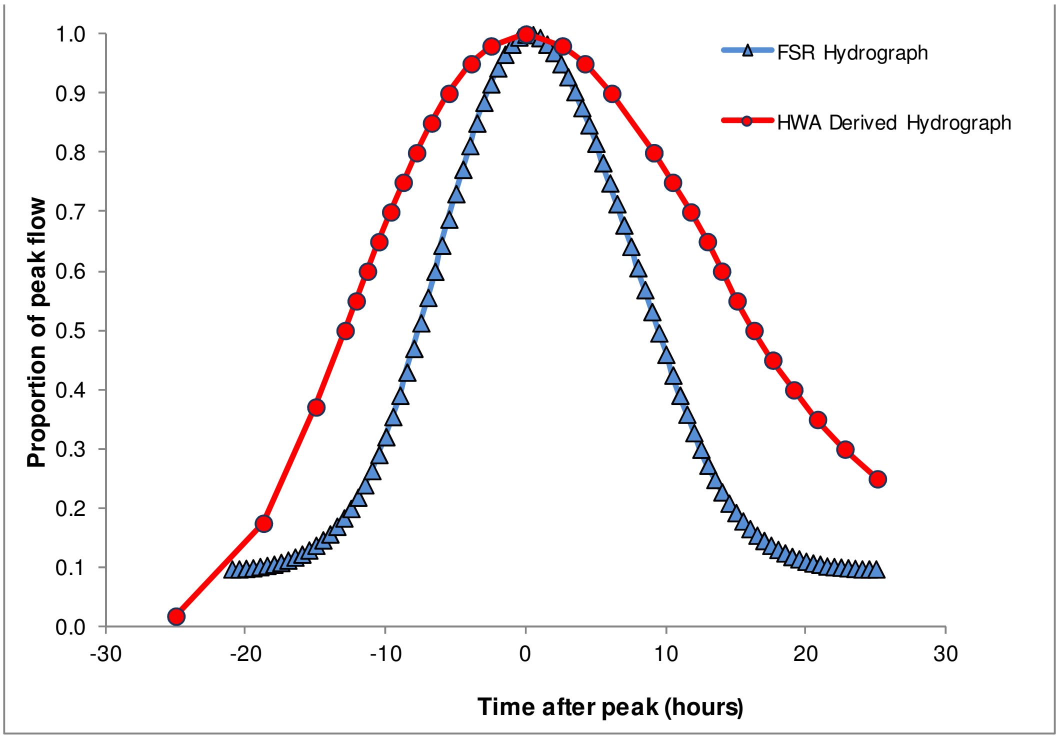
Rank	Date	Flow (m^3/s)	Rank	Date	Flow (m^3/s)
1	23/11/2009	19.37	11	05/02/1990	13.77
2	09/12/2007	18.01	12	05/12/2000	13.43
3	30/10/1989	16.37	13	08/02/2011	13.36
4	23/12/1999	15.14	14	29/10/2002	12.63
5	05/01/1991	14.85	15	11/12/1999	12.35
6	20/01/2005	14.50	16	28/01/1995	12.30
7	02/01/1999	14.47	17	10/02/2002	12.25
8	08/11/2010	14.29	18	24/01/2008	12.13
9	28/11/1999	14.14	19	24/11/1986	11.96
10	10/01/1998	14.10	20	01/12/1984	11.90

Parameters of the hydrograph

n	Tr (hours)	C	Xo	Yo
2.88	119.25	900.99	87.09	0.71

A number of events were discounted due to irregularities in the data or the HWA software sampling a peak which was on the rising or falling limb of a larger event. These have been replaced with other events and some events were trimmed to discard complex areas of multi-peaked hydrographs. The HWA parametric hydrograph is very much wider than that produced by the FSR Rainfall Runoff method. This was produced using a Gamma curve for the rising and initial receding limbs of the hydrograph, switching to a recession curve 87.09 hours after the peak.

Station 34029	Deel @ Knockadangan (227km^2)



Flood events used in the analysis

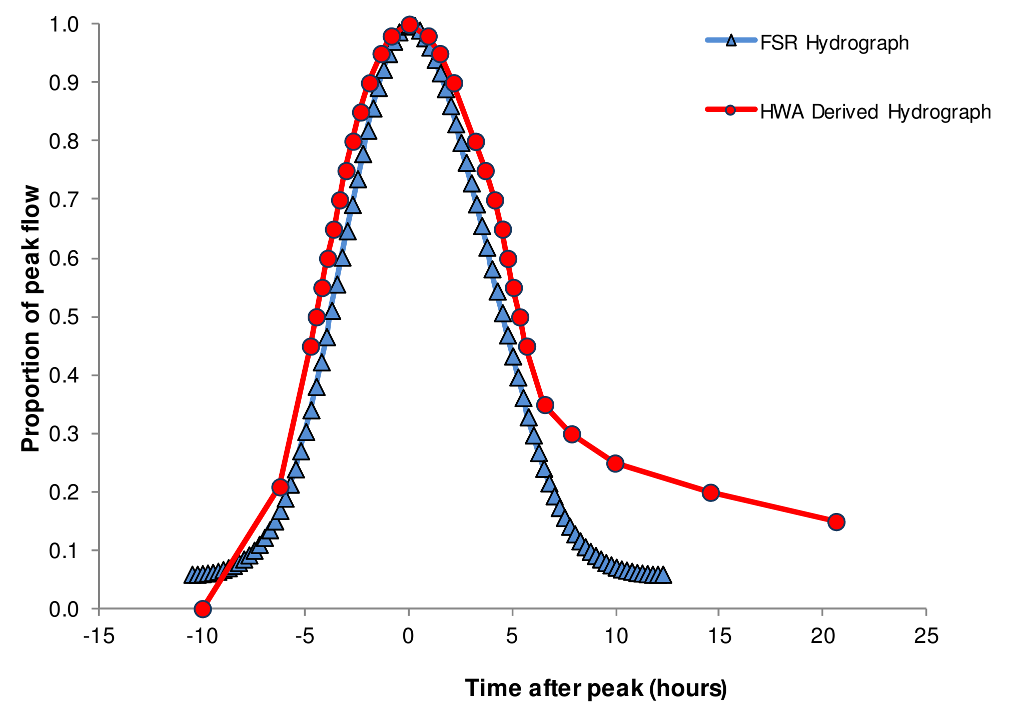
Rank	Date	Flow (m^3/s)	Rank	Date	Flow (m^3/s)
1	3/12/2006	151.48	11	07/02/2011	79.41
2	27/10/2002	111.11	12	20/11/2006	78.05
3	06/03/2007	106.83	13	21/10/2002	73.85
4	04/12/2001	102.39	14	14/08/2008	70.69
5	14/12/2006	97.03	15	05/04/2010	69.57
6	08/09/2010	91.75	16	31/01/2004	67.56
7	08/11/2010	90.45	17	16/08/2008	65.72
8	30/11/2006	83.94	18	09/01/2007	63.99
9	20/02/2002	82.96	19	04/11/2010	63.67
10	18/11/2009	79.65	20	10/10/2008	63.08

Parameters of the hydrograph

n	Tr (hours)	C	Xo	Yo
9.03	35.87	50.84	12.66	0.67

A number of events were discounted due to irregularities in the data or the HWA software sampling a peak which was on the rising or falling limb of a larger event. These have been replaced with other events and some events were trimmed to discard complex areas of multi-peaked hydrographs. The parametric HWA hydrograph is similar, but a little wider than that produced by the FSR Rainfall Runoff method, with a slower time to rise and a longer falling limb. This was produced using a Gamma curve for the rising and initial receding limbs, switching to a recession curve 12.67 hours after the peak.

Station 34031	Mullaghanoe @ Charlestown (23km^2)



Flood events used in the analysis

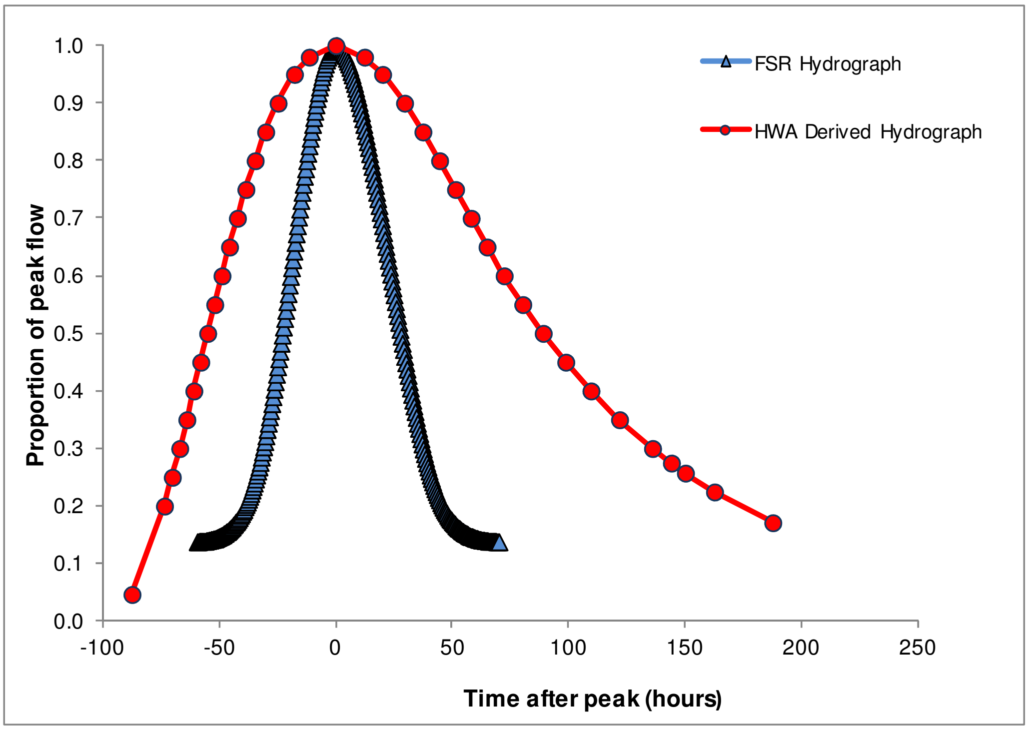
Rank	Date	Flow (m^3/s)	Rank	Date	Flow (m^3/s)
1	25/01/2009	10.80	11	8/11/2002	8.47
2	08/12/2007	10.30	12	09/02/2002	8.45
3	02/11/2002	9.74	13	25/05/2005	7.84
4	13/08/2008	9.68	14	19/02/2002	7.72
5	05/03/2007	9.53	15	21/09/2006	7.63
6	21/11/2009	9.33	16	12/12/2000	7.47
7	07/09/2010	8.71	17	27/10/2002	7.45
8	05/10/2001	8.64	18	08/11/2010	7.27
9	27/02/2000	8.59	19	10/11/2002	7.25
10	21/01/2008	8.54	20	10/10/2008	7.08

Parameters of the hydrograph

n	Tr (hours)	C	Xo	Yo
8.65	12.23	12.73	4.42	0.67

Many events at Charlestown were discounted due to periods of no data; this was often found during the higher events, therefore it is assumed this was due to logger failure. Extra, lower magnitude events have replaced these. The parametric HWA hydrograph is very similar to that produced by the FSR Rainfall Runoff method. This was produced using a Gamma curve for the rising and initial receding limbs, switching to a recession curve 4.42 hours after the peak. The latter receding limb is the non parametric HWA curve, given the poor fit of the recession curve after 6.5 hours.

Station 35001	Owenmore @ Ballynacarrow (300km²)



Flood events used in the analysis

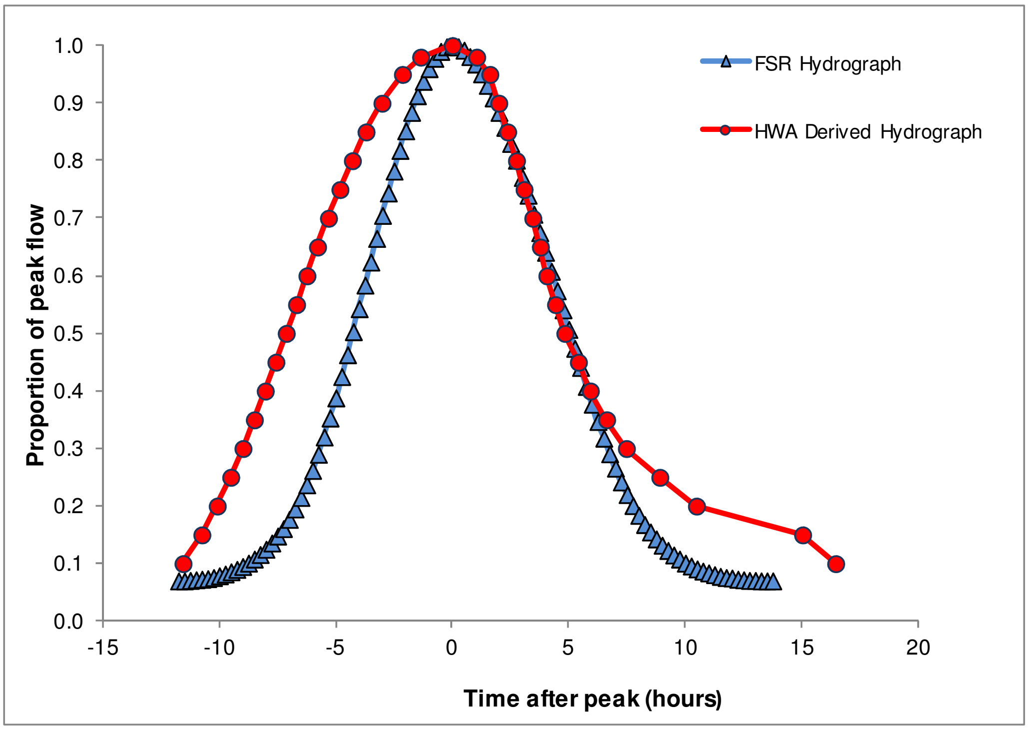
Rank	Date	Flow (m^3/s)	Rank	Date	Flow (m^3/s)
1	04/11/1968	48.78	11	20/09/1965	35.16
2	30/10/1989	44.83	12	28/11/1979	35.11
3	08/02/1990	39.23	13	11/10/1967	34.78
4	10/01/1992	38.88	14	11/03/1995	33.92
5	29/05/1985	38.58	15	03/01/1957	33.91
6	24/10/1967	38.04	16	18/10/1964	33.44
7	04/11/1980	36.60	17	23/11/1971	33.20
8	20/11/1965	36.46	18	30/09/1981	33.07
9	18/11/1978	36.32	19	09/10/1965	32.68
10	20/01/1965	35.59	20	17/11/1959	31.90

Parameters of the hydrograph

n	Tr (hours)	C	Xo	Yo
4.14	104.50	367.45	59.01	0.693

A number of events were discounted due to irregularities in the data or the HWA software sampling a peak which was on the rising or falling limb of a larger event. These have been replaced with other events and some events were trimmed to discard complex areas of multi-peaked hydrographs. The HWA parametric hydrograph is significantly wider than that produced by the FSR Rainfall Runoff method. This was produced using a Gamma curve for the rising and initial receding limbs of the hydrograph, switching to a recession curve 59.01 hours after the peak for the remaining receding limb.

Station 35002	Owenbeg @ Billa Bridge (89km^2)



Flood events used in the analysis

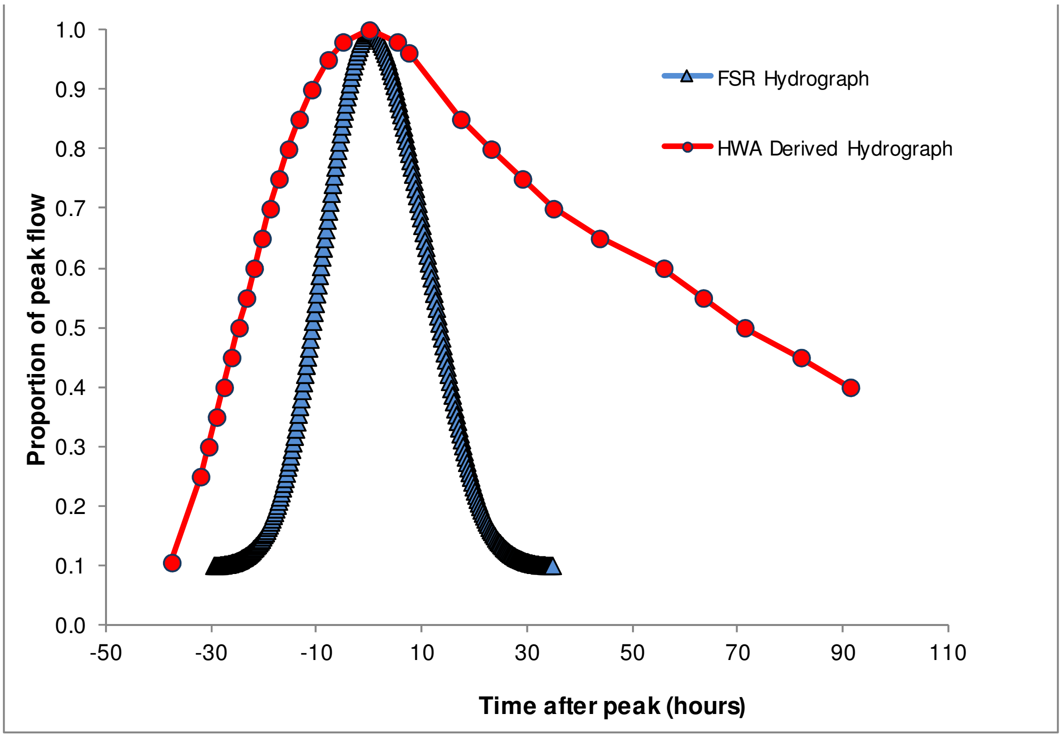
Rank	Date	Flow (m^3/s)	Rank	Date	Flow (m^3/s)
1	28/10/1989	69.30	11	20/08/1987	58.84
2	27/10/2002	66.85	12	04/11/1999	58.43
3	06/10/1990	66.85	13	06/08/1986	58.35
4	29/10/1989	62.46	14	16/11/2009	57.35
5	28/11/1999	61.64	15	03/11/2002	57.03
6	02/09/1988	61.24	16	24/10/1998	56.82
7	26/11/1979	60.55	17	12/10/1978	56.74
8	01/01/1991	59.44	18	11/02/1998	56.69
9	21/10/1998	59.14	19	21/09/1985	56.36
10	15/11/1978	59.09	20	28/11/1973	55.98

Parameters of the hydrograph

n	Tr (hours)	C	Xo	Yo
10.00	20.80	n/a	n/a	n/a

The 20 largest events on record were sampled with no events removed. A number of the sample events were trimmed in order to discard complex areas of multi-peaked hydrographs. The final HWA hydrograph has a similar width to that produced by the FSR Rainfall Runoff method. This was produced using a Gamma curve for the rising limb. The receding limb is the non parametric HWA curve, given the poor fit of the recession and gamma curves after the peak.

Station 35005	Ballysadare @ Ballysadare (640km^2)



Flood events used in the analysis

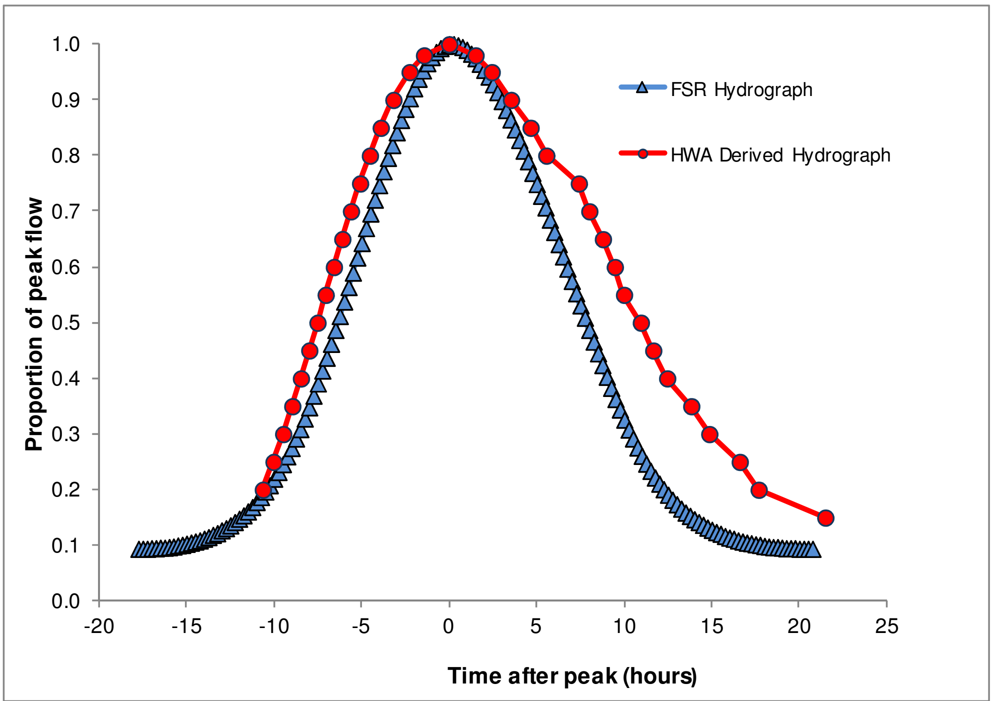
Rank	Date	Flow (m^3/s)	Rank	Date	Flow (m^3/s)
1	20/11/2009	142.42	11	29/11/1999	98.36
2	29/10/1989	131.12	12	09/01/1992	98.18
3	02/11/1968	126.39	13	10/12/1999	94.24
4	27/10/2002	114.97	14	08/01/2005	92.88
5	26/11/1979	114.09	15	10/01/1965	92.45
6	09/01/1968	112.33	16	14/12/2006	91.05
7	19/10/1954	111.64	17	11/03/1995	88.88
8	09/12/2007	105.13	18	03/02/2004	86.55
9	10/01/1998	103.26	19	2/11/1980	85.72
10	01/03/1955	102.99	20	28/11/1954	85.31

Parameters of the hydrograph

n	Tr (hours)	C	Xo	Yo
5.21	52.63	n/a	n/a	n/a

A number of events were discounted due to irregularities in the data or the HWA software sampling a peak which was on the rising or falling limb of a larger event. These have been replaced with other events and some events were trimmed to discard complex areas of multi-peaked hydrographs. The parametric HWA hydrograph is wider than that produced by the FSR Rainfall Runoff method. This was produced using a Gamma curve for the rising and initial receding limbs of the hydrograph, switching to the non parametric HWA curve, given the poor fit of the recession curve after 25 hours.

Station 35011	Bonet @ Dromahair (293km^2)



Flood events used in the analysis

Rank	Date	Flow (m^3/s)	Rank	Date	Flow (m^3/s)
1	22/10/1987	187.79	11	27/10/2002	146.82
2	28/11/1999	176.38	12	08/11/2002	142.37
3	02/09/1988	167.82	13	02/03/2000	141.70
4	22/12/1991	161.62	14	18/11/1965	138.38
5	06/08/1986	159.51	15	21/10/1998	138.34
6	05/12/1986	157.44	16	10/03/1995	136.86
7	28/10/1989	152.23	17	27/02/2000	133.27
8	08/01/1992	150.83	18	26/10/1995	132.65
9	06/10/1990	148.50	19	03/12/1999	131.80
10	26/01/1993	147.02	20	22/11/1998	130.87

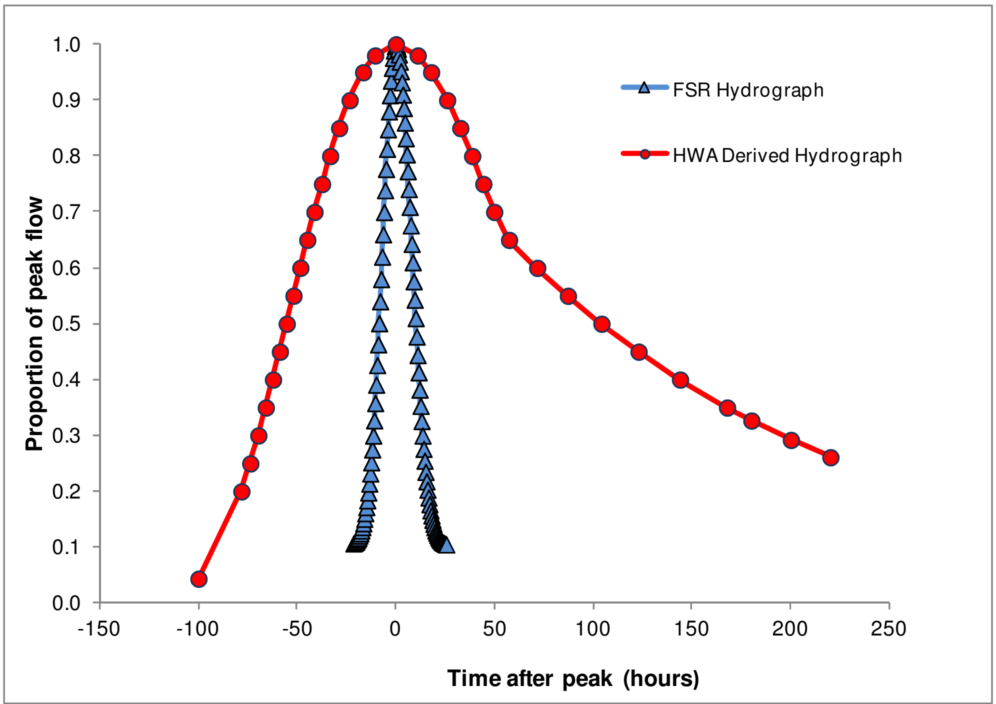
Parameters of the hydrograph

n	Tr (hours)	C	Xo	Yo
9.98	21.92	n/a	n/a	n/a

One event was discounted due to irregularities in the data. This was replaced with another event and some events were trimmed to discard complex areas of multi-peaked hydrographs. The parametric HWA hydrograph is very similar to that produced by the FSR Rainfall Runoff method. This was produced using a Gamma curve for the rising and initial receding limbs of the hydrograph, switching to the non parametric HWA curve, given the poor fit of the recession curve after 4.5 hours.

Flood width analysis summary sheet

Station 35012	Sligo River @ New Bridge (369km²)



Flood events used in the analysis

Rank	Date	Flow (m^3/s)	Rank	Date	Flow (m^3/s)
1	19/11/2009	184.11	11	25/02/2002	145.35
2	19/10/2011	182.47	12	23/01/2008	139.95
3	07/11/2009	172.74	13	08/02/2011	138.11
4	09/12/2007	167.97	14	17/08/2008	129.46
5	10/11/2002	166.85	15	05/11/2010	126.31
6	21/01/2005	166.62	16	23/09/2004	125.34
7	09/01/2007	159.08	17	01/02/2009	123.01
8	28/10/2002	156.68	18	06/05/2004	122.43
9	09/01/2005	154.29	19	22/05/2003	119.75
10	02/02/2004	146.19	20	27/05/2002	118.99

Parameters of the hydrograph

n	Tr (hours)	C	Xo	Yo
10.00	161.23	178.34	53.74	0.66

Analysis at this station was added after completion of the inception phase, when it became apparent that design hydrograph shapes for input to the HPW model at Sligo would be best represented using observed hydrograph shapes.

A number of events were discounted due to irregularities in the data or the HWA software sampling a peak which was on the rising or falling limb of a larger event. These have been replaced with other events. Some events were trimmed to discard complex areas of multi-peaked hydrographs. The HWA parametric hydrograph is wider than that produced by the FSR Rainfall Runoff method. This was produced using a Gamma curve for the rising and initial receding limbs of the hydrograph, switching to a recession curve 57 hours after the peak for the remaining receding limb.

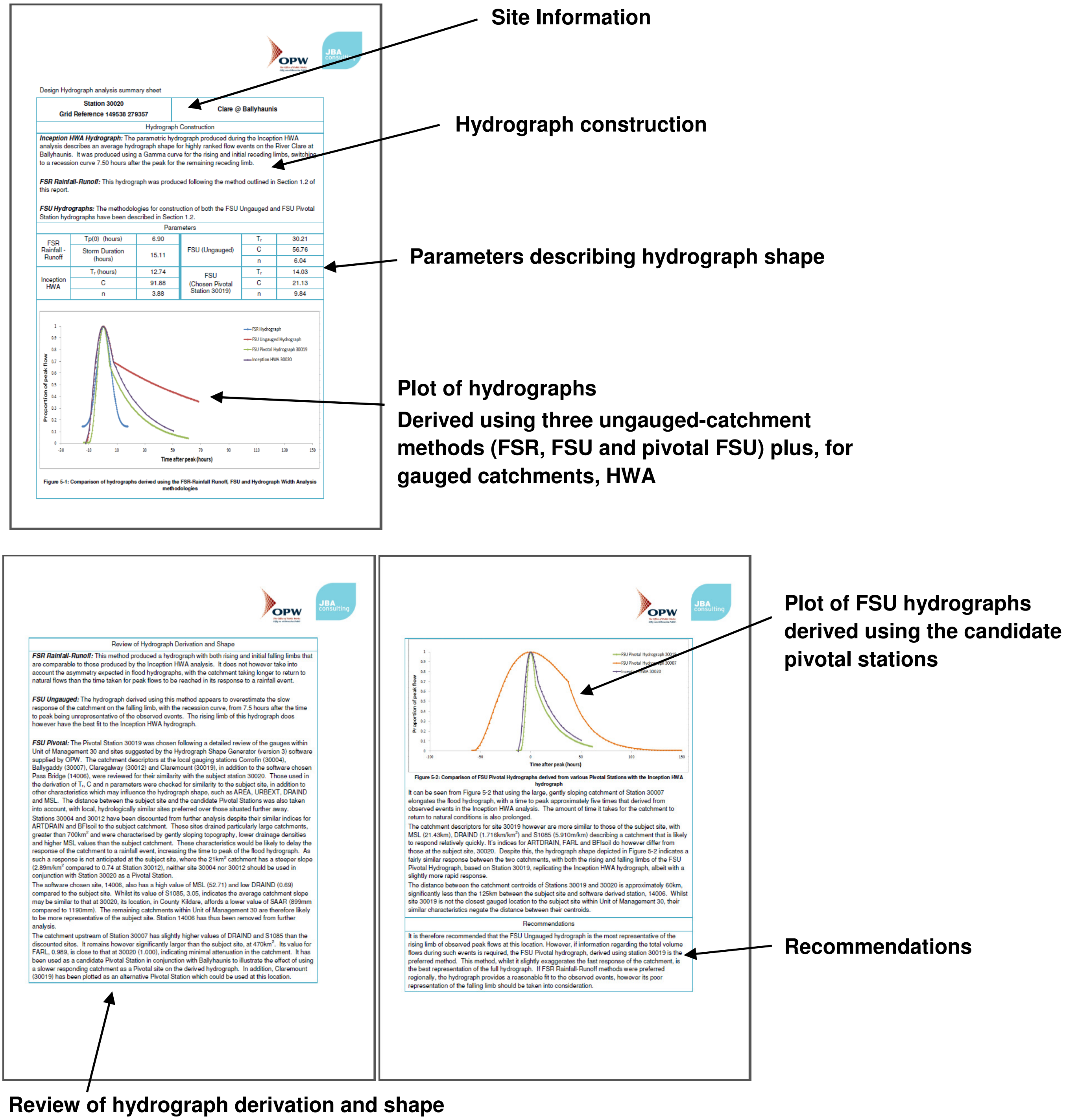
E Comparison of hydrograph shapes

Introduction to design flood hydrograph comparison summary sheets

This appendix provides a comparison of alternative design hydrograph shapes at a sample of five gauged and five ungauged catchments across the Western RBD.

For an explanation of the methods applied, please refer to Section 6.2 and 6.3 of this report. The ungauged variants of the FSR and FSU methods were applied at all ten sites. In addition, at the gauged sites, the FSU methods of averaging the widths of observed hydrographs (HWA) was applied.

Information provided in the summary sheets



Design Hydrograph analysis summary sheet

Station 30020 **Grid Reference 149538 279357**	**Clare @ Ballyhaunis**

Hydrograph Construction

Inception HWA Hydrograph: The parametric hydrograph produced during the Inception HWA analysis describes an average hydrograph shape for highly ranked flow events on the River Clare at Ballyhaunis. It was produced using a Gamma curve for the rising and initial receding limbs, switching to a recession curve 7.50 hours after the peak for the remaining receding limb.

Parameters

FSR Rainfall - Runoff	Tp(0) (hours)	6.90	FSU (Ungauged)	T_r	30.21
	Storm Duration (hours)	15.11		C	56.76
				n	6.04
Inception HWA	T_r (hours)	12.74	FSU (Chosen Pivotal Station 30019)	T_r	14.03
	C	91.88		C	21.13
	n	3.88		n	9.84

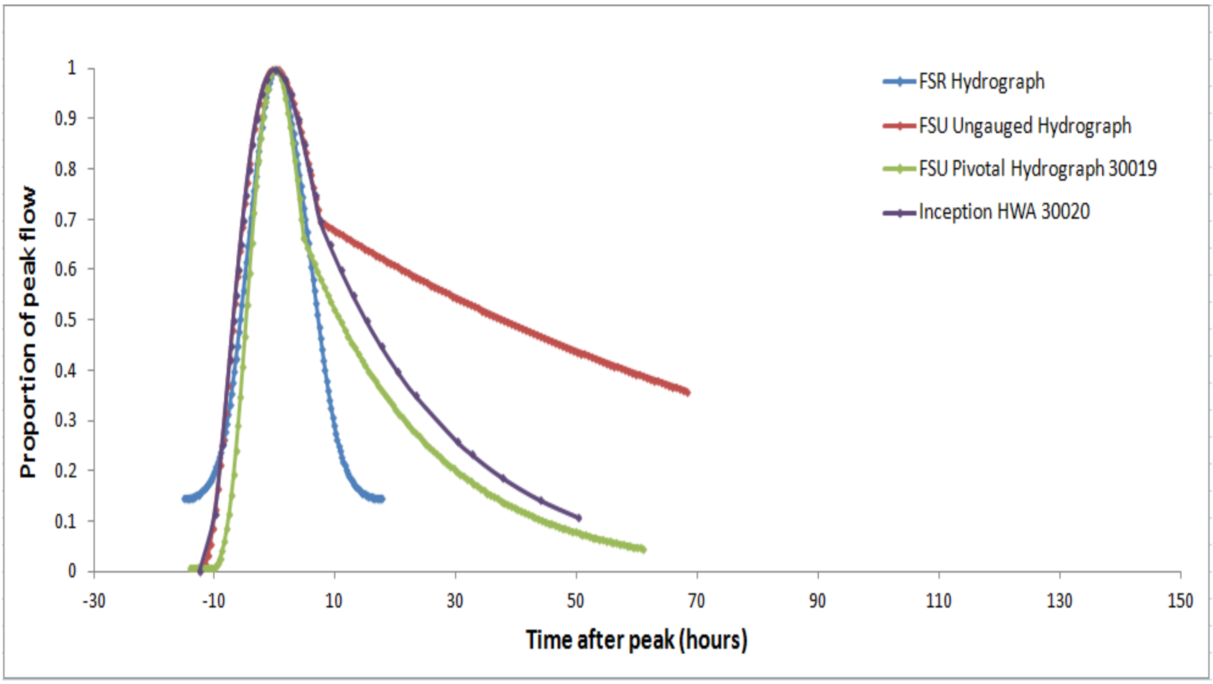


Figure E1-1: Comparison of hydrographs derived using the FSR-Rainfall Runoff, FSU and Hydrograph Width Analysis methodologies

Review of Hydrograph Derivation and Shape
FSR Rainfall-Runoff: This method produced a hydrograph with both rising and initial falling limbs that are comparable to those produced by the Inception HWA analysis. It does not however take into account the asymmetry expected in flood hydrographs, with the catchment taking longer to return to natural flows than the time taken for peak flows to be reached in its response to a rainfall event. ***FSU Ungauged:*** The hydrograph derived using this method appears to overestimate the slow response of the catchment on the falling limb, with the recession curve, from 7.5 hours after the time to peak being unrepresentative of the observed events. The rising limb of this hydrograph does however have the best fit to the Inception HWA hydrograph. ***FSU Pivotal:*** The Pivotal Station 30019 was chosen following a detailed review of the gauges within Unit of Management 30 and sites suggested by the Hydrograph Shape Generator (version 3) software supplied by OPW. The catchment descriptors at the local gauging stations Corrofin (30004), Ballygaddy (30007), Claregalway (30012) and Claremount (30019), in addition to the software chosen Pass Bridge (14006), were reviewed for their similarity with the subject station 30020. Those used in the derivation of T_r, C and n parameters were checked for similarity to the subject site, in addition to other characteristics which may influence the hydrograph shape, such as AREA, URBEXT, DRAIND and MSL. The distance between the subject site and the candidate Pivotal Stations was also taken into account, with local, hydrologically similar sites preferred over those situated further away. Stations 30004 and 30012 have been discounted from further analysis despite their similar indices for ARTDRAIN and BFIsoil to the subject catchment. These sites drained particularly large catchments, greater than 700km^2 and were characterised by gently sloping topography, lower drainage densities and higher MSL values than the subject catchment. These characteristics would be likely to delay the response of the catchment to a rainfall event, increasing the time to peak of the flood hydrograph. As such a response is not anticipated at the subject site, where the 21km^2 catchment has a steeper slope (2.89m/km compared to 0.74 at Station 30012), neither site 30004 nor 30012 should be used in conjunction with Station 30020 as a Pivotal Station. The software chosen site, 14006, also has a high value of MSL (52.71) and low DRAIND (0.69) compared to the subject site. Whilst its value of S1085, 3.05, indicates the average catchment slope may be similar to that at 30020, its location, in County Kildare, affords a lower value of SAAR (899mm compared to 1190mm). The remaining catchments within Unit of Management 30 are therefore likely to be more representative of the subject site. Station 14006 has thus been removed from further analysis. The catchment upstream of Station 30007 has slightly higher values of DRAIND and S1085 than the discounted sites. It remains however significantly larger than the subject site, at 470km^2. Its value for FARL, 0.989, is close to that at 30020 (1.000), indicating minimal attenuation in the catchment. It has been used as a candidate Pivotal Station in conjunction with Ballyhaunis to illustrate the effect of using a slower responding catchment as a Pivotal site on the derived hydrograph. In addition, Claremount (30019) has been plotted as an alternative Pivotal Station which could be used at this location.

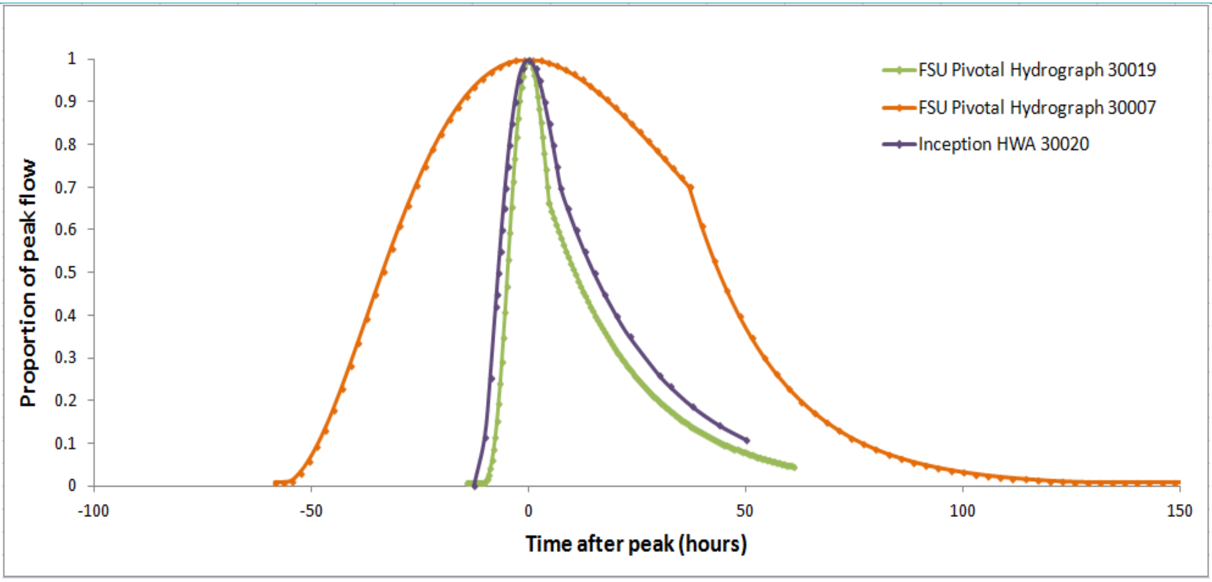


Figure E1-2: Comparison of FSU Pivotal Hydrographs derived from various Pivotal Stations with the Inception HWA hydrograph

It can be seen from Figure E1-2 that using the large, gently sloping catchment of Station 30007 elongates the flood hydrograph, with a time to peak approximately five times that derived from observed events in the Inception HWA analysis. The amount of time it takes for the catchment to return to natural conditions is also prolonged.

The catchment descriptors for site 30019 however are more similar to those of the subject site, with MSL (21.43km), DRAIND (1.716km/km^2) and S1085 (5.910m/km) describing a catchment that is likely to respond relatively quickly. It's indices for ARTDRAIN, FARL and BFIsoil do however differ from those at the subject site, 30020. Despite this, the hydrograph shape depicted in Figure E1-2 indicates a fairly similar response between the two catchments, with both the rising and falling limbs of the FSU Pivotal Hydrograph, based on Station 30019, replicating the Inception HWA hydrograph, albeit with a slightly more rapid response.

The distance between the catchment centroids of Stations 30019 and 30020 is approximately 60km, significantly less than the 125km between the subject site and software derived station, 14006. Whilst site 30019 is not the closest gauged location to the subject site within Unit of Management 30, their similar characteristics negate the distance between their centroids.

Recommendations

It is therefore recommended that the FSU Ungauged hydrograph is the most representative of the rising limb of observed peak flows at this location. However, if information regarding the total volume flows during such events is required, the FSU Pivotal hydrograph, derived using station 30019 is the preferred method. This method, whilst it slightly exaggerates the fast response of the catchment, is the best representation of the full hydrograph. If FSR Rainfall-Runoff methods were preferred regionally, the hydrograph provides a reasonable fit to the observed events, however its poor representation of the falling limb should be taken into consideration.

Design Hydrograph analysis summary sheet

Station 32011 **Grid Reference 80906 280601**	**Bunowen @ Louisburg Weir**

Hydrograph Construction

Inception HWA Hydrograph: The parametric hydrograph produced during the Inception HWA analysis describes an average hydrograph shape for highly ranked flow events on the River Bunowen at Louisburg Weir. It was produced using a Gamma curve for the rising and initial receding limbs of the hydrograph, switching to a recession curve 2.81 hours after the peak flow for the remaining receding limb.

Parameters

FSR Rainfall - Runoff	Tp(0) (hours)	4.51	FSU (Ungauged)	T_r	13.93
	Storm Duration (hours)	11.79		C	7.91
				n	10.21
Inception HWA	T_r (hours)	7.59	FSU (Chosen Pivotal Station 32004)	T_r	6.17
	C	15.66		C	9.80
	n	8.30		n	10.00

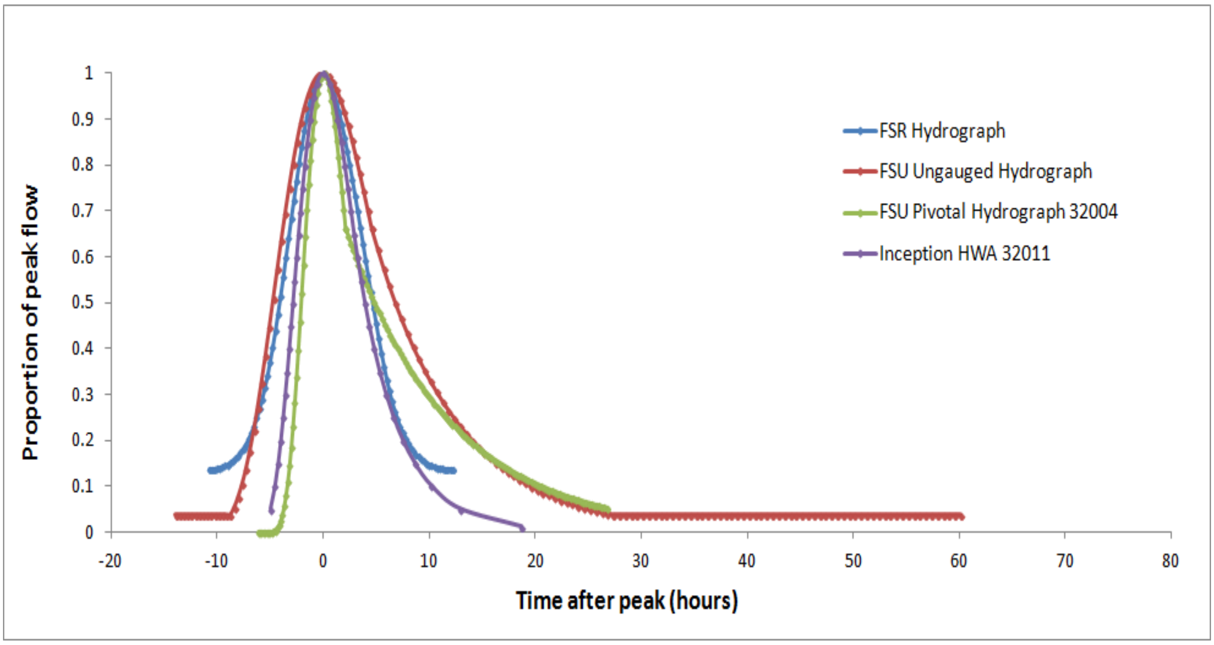


Figure E2-1: Comparison of hydrographs derived using the FSR-Rainfall Runoff, FSU and Hydrograph Width Analysis methodologies

FSR Rainfall-Runoff: The FSR Rainfall-Runoff method produced a hydrograph with a falling limb that is very similar to that produced by the Inception HWA analysis. The rising limb of the FSR Rainfall-Runoff hydrograph however achieves a poorer fit to the steep limb of the Inception HWA hydrograph.

FSU Ungauged: This mirrors the FSR Rainfall-Runoff hydrograph, having a similar fit on the rising limb and upper falling limb. The recession curve, from 4.6 hours after the time to peak, is unrepresentative of this quickly responding catchment.

FSU Pivotal: The Pivotal Station 32004 was chosen following a detailed review of the gauges within Unit of Management 32 and sites suggested by the Hydrograph Shape Generator (version 3) software supplied by OPW. The catchment descriptors at the local gauging stations Clifden (32004), Coolloughra (32006) and Newport Weir (32012), in addition to the software chosen Ballymullen (23012), were reviewed for their similarity with the subject station 32011. Those used in the derivation of T_r, C and n parameters were checked for similarity to the subject site, in addition to other characteristics which may influence the hydrograph shape, such as AREA, URBEXT, DRAIND and MSL. The distance between the subject site and the candidate Pivotal Stations was also taken into account, with local, hydrologically similar sites preferred over those situated further away.

Station 32012 has been discounted from further analysis due to a particularly low value of FARL, 0.843, compared to that of the subject station, 0.986, as a result of Beltra Lough in the upper catchment. This lake may attenuate peak flows and increase the lag time, causing a hydrograph at Newport Weir that is dissimilar from that expected at Louisburgh Weir where attenuation is less severe. The remaining stations have been used as candidate Pivotal Stations in conjunction with Louisburgh Weir, and their hydrographs plotted for examination:

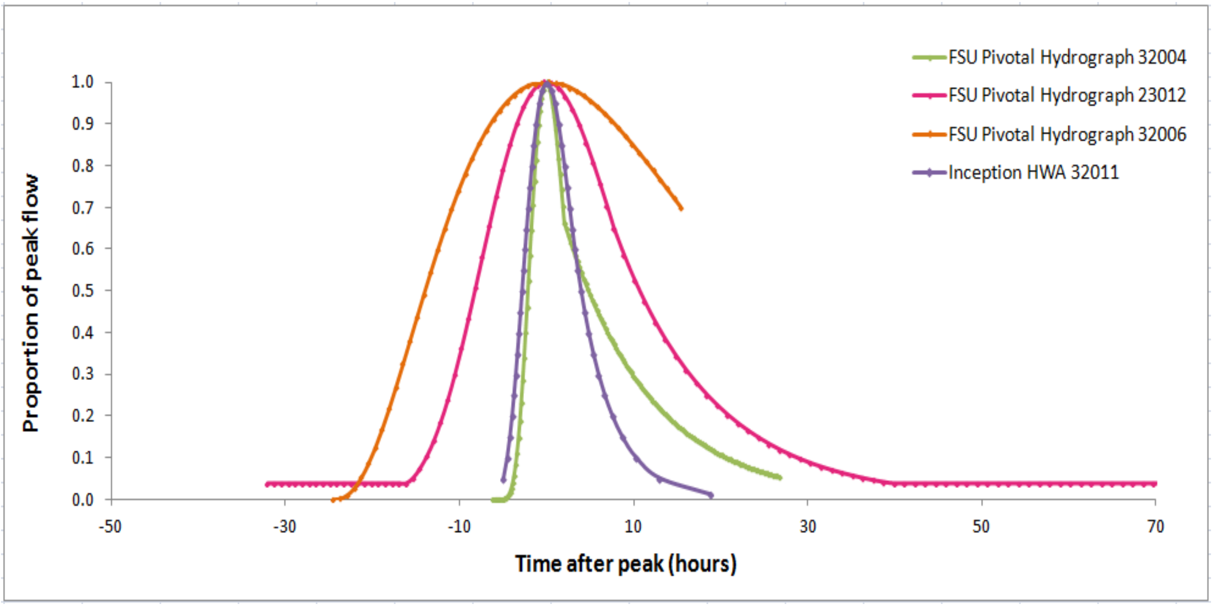


Figure E2-2: Comparison of FSU Pivotal Hydrographs derived from various Pivotal Stations with the Inception HWA hydrograph

The catchment descriptors for these three sites are all fairly similar to the subject site, with station 32006 being the least representative, as BFIsoil and SAAR were larger than at 32011. At station 23012, only URBEXT was particularly high in the Pivotal Station catchment compared to the subject

site (2.43 and 0.15 respectively), whilst station 32004 is most similar, with only DRAIND and ALLUV slightly higher and lower than the values at the subject site respectively. The AREA of the catchments at the subject site and Station 32004 are 70.1km^2 and 32.4km^2 respectively, and the distance between their centroids is approximately 26km. This is a relatively small distance and confirms that in this case, the most hydrologically similar catchment is situated relatively near to the subject site. Whilst the catchments are broadly hydrologically similar, the hydrographs produced from using them as candidate Pivotal Stations suggest that the descriptors BFIsoil, SAAR and URBEXT have a greater influence on the hydrograph shape than DRAIND and ALLUV. This is represented in Figure E2-2, where Pivotal Hydrographs utilising data from Station 23012 and 32006 indicate catchments with slower response times than expected at the subject site. The FSU Pivotal hydrograph, incorporating data from Station 32011, sufficiently describes a faster responding catchment, replicating the rising limb of the Inception HWA hydrograph. The falling limb of the FSU Pivotal 32004 hydrograph is also a good fit to the typical shape derived from observed events for the first 5 hours after the peak flow. Beyond this, it takes slightly longer for the FSU derived hydrograph to return to baseflow conditions, however the fit is not particularly dissimilar from the observed events.
Recommendations
It is therefore recommended that the FSU Pivotal hydrograph, derived using station 32004, is the most representative of the observed hydrographs at this location. Whilst it overestimates the time it takes for the catchment to return to natural flows after the peak event, its representation of the rising limb is significantly better than the hydrographs derived using other methods. If FSR Rainfall-Runoff methods were preferred regionally, the hydrograph provides a reasonable fit to the observed events however the slightly longer lag time should be taken into consideration.

Design Hydrograph analysis summary sheet

Station 34007 **Grid Reference 112087 316052**	**Deel @ Ballycarroon**

Hydrograph Construction

Inception HWA Hydrograph: The parametric hydrograph produced during the Inception HWA analysis describes an average hydrograph shape for highly ranked flow events on the River Deel at Ballycarroon. It was produced using a Gamma curve for the rising and initial receding limbs of the hydrograph, switching to a recession curve 7.47 hours after the peak flow for the remaining receding limb.

Parameters

FSR Rainfall - Runoff	Tp(0) (hours)	7.16	FSU (Ungauged)	T_r	21.30
	Storm Duration (hours)	18.54		C	9.26
				n	9.56
Inception HWA	T_r	20.98	FSU (Chosen Pivotal Station 27001)	T_r	17.72
	C	39.11		C	11.24
	n	8.89		n	5.00

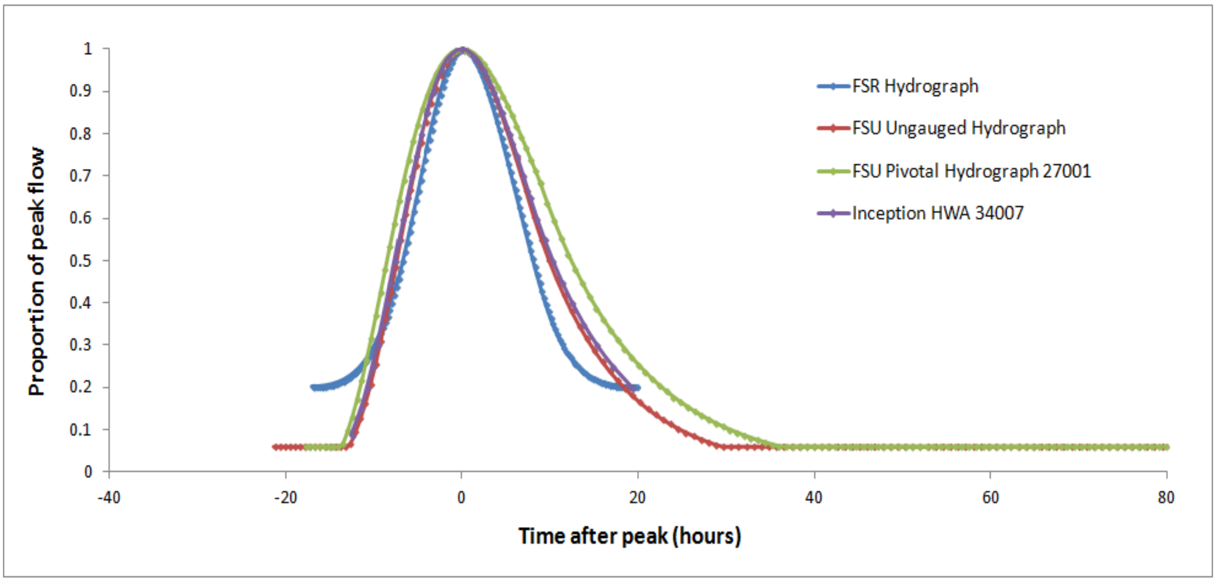


Figure E3-1: Comparison of hydrographs derived using the FSR-Rainfall Runoff, FSU and Hydrograph Width Analysis methodologies

Review of Hydrograph Derivation and Shape

FSR Rainfall-Runoff: This method produced a hydrograph with a rising limb that is similar, but slightly steeper, than that produced by the Inception HWA analysis. The falling limb of the FSR Rainfall-Runoff hydrograph also describes a more responsive catchment than that of the Inception HWA hydrograph.

FSU Ungauged: The hydrograph gives a particularly good fit to both the rising and falling limbs of the observed events, representing the responsive nature of the catchment and its return to natural flows.

FSU Pivotal: The Pivotal Station 27001 was chosen following a detailed review of the gauges within Unit of Management 34 and sites suggested by the Hydrograph Shape Generator (version 3) software supplied by OPW. The catchment descriptors at the local gauging stations Rahans (34001), Turlough (34018) and Lannagh (34073), in addition to the automatically selected station Inch Bridge (27001) were reviewed for their similarity with the subject station 34007. Those used in the derivation of T_r, C and n parameters were checked for similarity to the subject site, in addition to other characteristics which may influence the hydrograph shape, such as AREA, URBEXT, DRAIND and MSL. The distance between the subject site and the candidate Pivotal Stations was also taken into account, with local, hydrologically similar sites preferred over those situated further away. Station 34001 has been discounted from further analysis due to its low value of FARL, 0.85, compared to that of the subject station 0.978, as a result of Loughs Conn and Cullin, through which a substantial proportion of the catchment drains. Station 34073, in the lower reaches of the River Moy, is also affected by various upstream waterbodies, decreasing FARL to 0.825. These features may attenuate peak flows and increase the lag time, causing hydrograph shapes at Rahans and Lannagh that deviate from that expected at Ballycarroon, where less attenuation of flows occurs. In addition, the URBEXT value for Rahans is much higher, at 12.08 compared to 0.00 at the subject site, and the BFIsoil value for Lannagh is 0.763, whereas at Ballycarroon it is 0.349. These characteristics are likely to result in differing volumes of runoff in these catchments compared to the site of interest and therefore they have not been included in further analysis of candidate Pivotal Stations.

Station 34018 has been investigated in the Inception HWA stage, with the derivation of T_r, C and n parameters. However, whilst the site's location makes it preferable as a Pivotal Station, a number of catchment descriptors are dissimilar. In particular, ARTDRAIN, URBEXT and BFIsoil are higher at Turlough than Ballycarroon:

Catchment Descriptor	Ballycarroon (34007)	Turlough (34018)
ARTDRAIN (%)	0.00	13.70
URBEXT (%)	0.00	5.53
BFIsoil	0.349	0.750

These characteristics imply that using this site as a Pivotal Station may make the hydrograph respond quicker to rainfall as a result of greater runoff volumes and faster routing of flows to the main watercourse. These features are not expected at Ballycarroon and therefore Station 34018 has also been discounted as a candidate Pivotal Station.

The remaining station, 27001, chosen by the Hydrograph Shape Generator software as being most similar to the subject site, has been reviewed manually. The values of ALLUV, ARTDRAIN, S1085, URBEXT, FARL and BFIsoil are consistent with those at Ballycarroon. The AREA of the catchments at the subject site and Station 27001 are 151.7km^2 and 46.7km^2 respectively, and the distance between their centroids is approximately 140km. Whilst this Pivotal Site is therefore located some distance from the subject catchment, its characteristics make it the most suitable site for this analysis.

The FSU Pivotal hydrograph, incorporating data from Station 27001, whilst representing the hydrograph shape of the Inception HWA well, is slightly slower responding than the FSU Ungauged hydrograph.

Recommendations
It is therefore recommended that the FSU Ungauged hydrograph is used, as it is the most representative of flood events at this location. This hydrograph estimates the response time of the catchment and the volume of water well, capturing the overall characteristics of a typical event at Station 34007. If the FSU Ungauged method was not the preferred regional method, the FSR Rainfall-Runoff and FSU Pivotal hydrographs, utilising data from Station 27001, could be used at this location as they give a relatively good fit to the observed data. The former would however infer the catchment is more responsive than has been observed, whilst the latter indicates a slower responding catchment and the conveyance of a greater volume of flood water.

Design Hydrograph analysis summary sheet

Station 34018 Grid Reference 120613 293565			Castlebar @ Turlough		
Hydrograph Construction					
Inception HWA Hydrograph: The parametric hydrograph produced during the Inception HWA analysis describes an average hydrograph shape for highly ranked flow events on the Castlebar River at Turlough. The process involved discounting a number of events with suspicious data and the removal of events with multi-peaked hydrographs. The resulting hydrograph was produced using a Gamma curve for the rising limb and initial receding limb, switching to the non parametric Hydrograph Width Analysis curve at 25.7 hours after the peak, given the poor fit of the recession and Gamma curves. Caution should be exerted when comparing hydrographs produced using alternative methods with this Inception HWA hydrograph.					
Parameters					
FSR Rainfall - Runoff	Tp(0) (hours)	6.26	FSU (Ungauged)	T_r	45.41
	Storm Duration (hours)	15.98		C	529.60
				n	2.02
Inception HWA	T_r	119.25	FSU (Chosen Pivotal Station 34003)	T_r	68.27
	C	900.99		C	n/a
	n	2.88		n	2.85

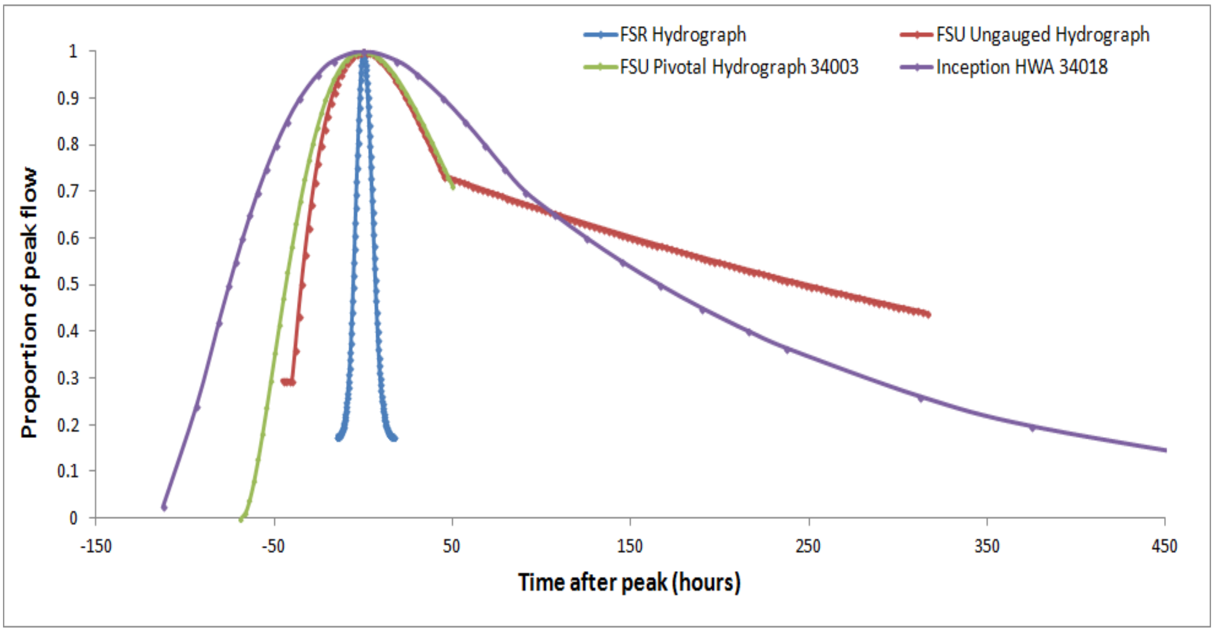


Figure E4-1: Comparison of hydrographs derived using the FSR-Rainfall Runoff, FSU and Hydrograph Width Analysis methodologies

Review of Hydrograph Derivation and Shape

FSR Rainfall-Runoff: This method produced a hydrograph that does not represent peak flow events at Turlough. It estimated a time to peak of 6.5 hours, very much shorter than that implied by observed hydrographs.

FSU Ungauged: This hydrograph also has a poor fit to the recorded events, estimating flows to be routed through the catchment more quickly than observed. In addition, the recession curve, from 45 hours after the time to peak, is very shallow as a result of the low FARL value at this location (0.732).

FSU Pivotal: The Pivotal Station 34003 was chosen following a detailed review of the gauges within Unit of Management 34 and sites suggested by the Hydrograph Shape Generator (version 3) software supplied by OPW. The catchment descriptors at the local gauging stations Rahans (34001), Foxford (34003), Ballylahan (34004), Charlestown (34031) and Lannagh (34073) were reviewed for their similarity with the subject station 34018. The Hydrograph Shape Generator software automatically selected the parameters at 34018 given the catchment characteristics matched those describing the gauged subject site. Given this analysis requires treatment of the site as an ungauged location, this station was removed from the list of possible Pivotal Stations and alternative sites were examined for their suitability.

The catchment descriptors used in the derivation of T_r, C and n parameters were checked for similarity to the subject site, in addition to other characteristics which may influence the hydrograph shape, such as AREA, URBEXT, DRAIND and MSL. The distance between the subject site and the potential Pivotal Stations was also taken into account, with local, hydrologically similar sites preferred over those situated further away.

Stations 34004, 34031 and 34073 have not been analysed in further detail as a number of their catchment descriptors are dissimilar to those for the subject site, potentially producing unrealistic hydrograph shapes. For sites 34001 and 34031, considerable differences were noted in BFIsoil, URBEXT, FARL and ARTDRAIN to those at 34018:

Catchment Descriptor	Turlough (34018)	Ballylahan (34004)	Charlestown (34031)
BFIsoil	0.750	0.485	0.330
URBEXT (%)	5.53	0.81	0.62
FARL	0.732	0.959	1.000
ARTDRAIN (%)	13.70	0.00	0.00

Station 34073, whilst having a lower value of FARL (0.85), mirroring the greater attenuation expected at the subject site, has a poor match for ARTDRAIN, URBEXT, ALLUV and BFIsoil. For this reason it has also been excluded from further analysis. The remaining stations, 34001 and 34003 have more comparable catchment descriptors to station 34018 and therefore have been used to derive candidate Pivotal Hydrographs which are plotted below:

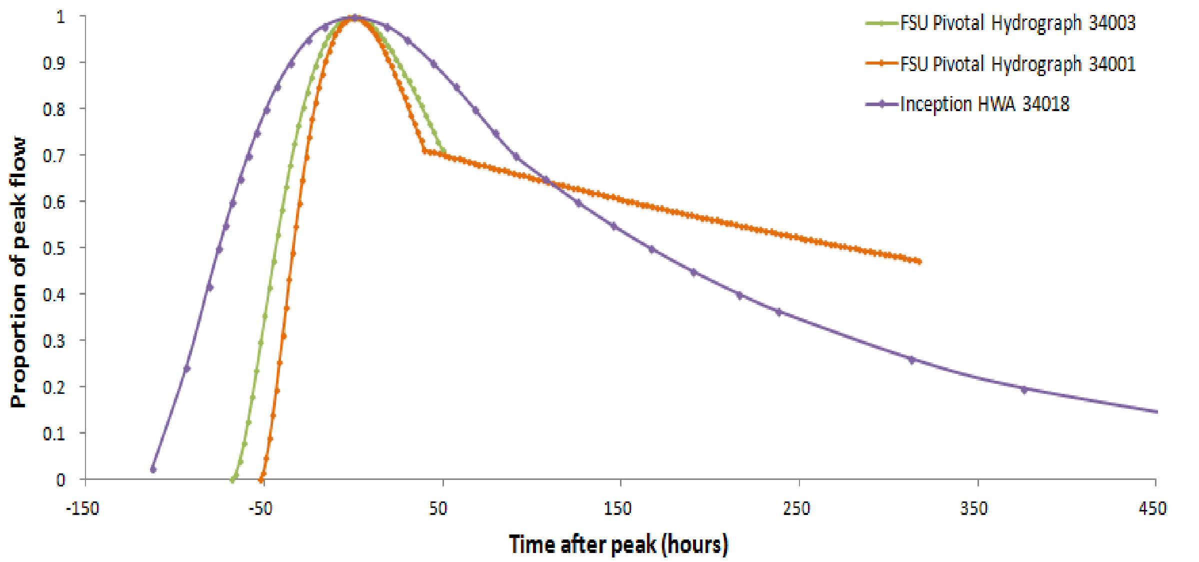


Figure E4-2: Comparison of FSU Pivotal Hydrographs derived from various Pivotal Stations with the Inception HWA hydrograph

Whilst the values of ARTDRAIN, FARL, BFIsoil and DRAIND are more appropriate at these sites, values of URBEXT (≈ 0.8) remain much lower than at 34018. Typically, more urban areas induce a shorter time to peak and a steeper hydrograph due to the greater volume of runoff and faster routing of water to the main watercourse. The observed events at Turlough do not reflect this process though given the URBEXT value of 5.5 indicates the catchment is still predominantly rural. Given the subject catchment is also much smaller and steeper than these potential Pivotal Sites, it is expected that significant attenuation by Castlebar Lough causes the longer lag time observed at the subject location. However, as the parameters used in the FSU derivation utilise FARL, this analysis may indicate that the methodology is unable to accurately represent the degree of attenuation in catchments containing large waterbodies.

The FSU Pivotal hydrograph, incorporating data from Station 34003, whilst underestimating the lag time, remains the best fit to the observed data. It may be disconcerting that using the FSU Pivotal method at this location, utilising both site specific information and data from local gauges, is unable to reproduce either the rising limb or falling limb of the Inception HWA hydrograph. However, the uncertainty in the derivation of the Inception HWA hydrograph outlined in Hydrograph Construction above, implies that confidence in the shape of this hydrograph is limited.

Recommendations

As noted in the inception report, the Turlough at Castlebar appears to experience flood hydrographs that are much more prolonged than expected for a catchment of its size. A more detailed investigation into the hydraulics of the watercourse (including backwater effects) is being carried out as part of the hydraulic modelling study, and a decision on the design flood hydrograph will be made after that. Neither the FSU Ungauged Hydrograph nor the FSR Rainfall-Runoff methodologies appear to be suitable. The FSU pivotal hydrograph provides little improvement on the ungauged hydrograph.

Station 35002 Grid Reference 163917 325724	Owenbeg @ Billa Bridge
Hydrograph Construction	

Inception HWA Hydrograph: The parametric hydrograph produced during the Inception HWA analysis describes an average hydrograph shape for highly ranked flow events on the Owenbeg River at Billa Bridge. It was produced using a Gamma curve for the rising limb, with the receding limb derived using the non parametric Hydrograph Width Analysis curve, given the poor fit of the recession and Gamma curves after the peak.

Parameters

FSR Rainfall - Runoff	Tp(0) (hours)	5.13	FSU (Ungauged)	T_r	22.06
	Storm Duration (hours)	12.20		C	35.79
				n	6.64
Inception HWA	T_r	20.80	FSU (Chosen Pivotal site 35011)	T_r	21.92
	C	n/a		C	n/a
	n	10.00		n	9.98

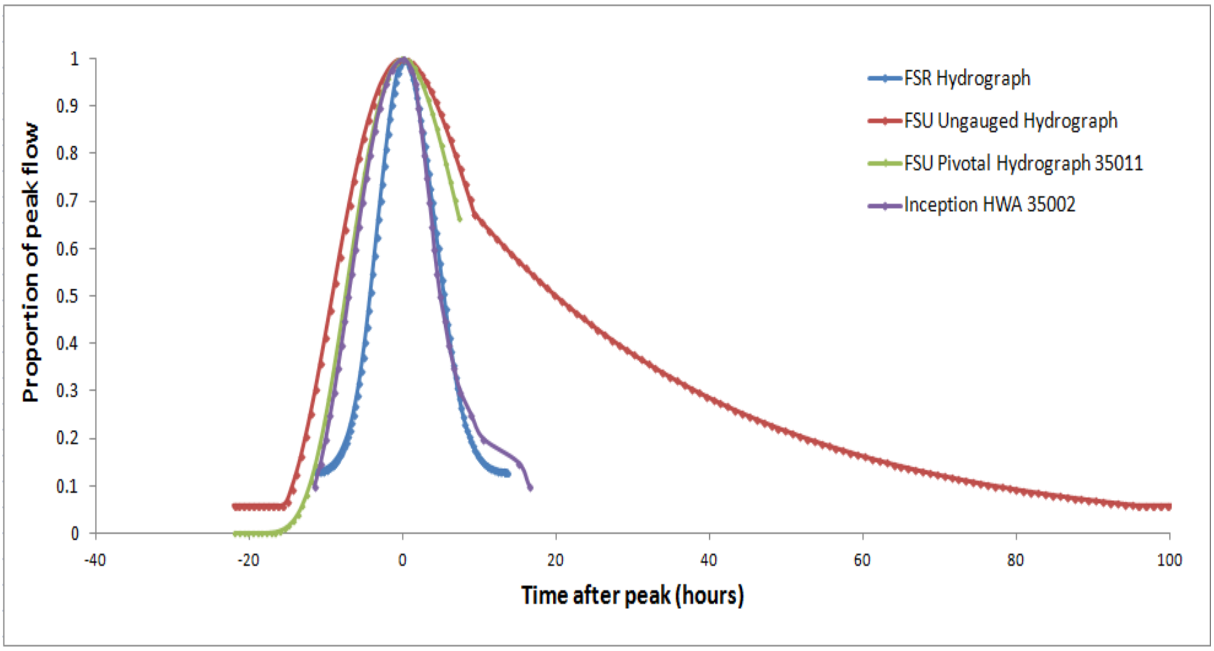


Figure E5-1: Comparison of hydrographs derived using the FSR-Rainfall Runoff, FSU and Hydrograph Width Analysis methodologies

FSR Rainfall-Runoff: This method produced a hydrograph with a falling limb that is very similar to that produced by the Inception HWA analysis. The rising limb of the FSR Rainfall-Runoff hydrograph however achieves a poorer fit to the steep limb of the Inception HWA hydrograph.

The FSU derived hydrographs do not replicate this similarity in the falling limb, with flows taking a longer time to be routed through the catchment. They do however illustrate a better fit to the rising limb than the FSR Rainfall-Runoff derived hydrograph.

FSU Ungauged:. The FSU Ungauged hydrograph describes a catchment which is slightly less responsive on the rising limb than the observed events of the Inception HWA hydrograph. In addition, the recession curve, from 9.3 hours after the time to peak, is unrepresentative of this quickly responding catchment.

FSU Pivotal: The Pivotal Station 35011 was chosen following a detailed review of the gauges within Unit of Management 35 and sites suggested by the Hydrograph Shape Generator (version 3) software supplied by OPW. The catchment descriptors at the local gauging stations Ballynacarrow (35001), Ballygrania (35003), Ballysadare (35005), and Dromahair (35011) were reviewed for their similarity with the subject station 35002.

The catchment descriptors used in the derivation of T_r, C and n parameters were checked for similarity to the subject site, in addition to other characteristics which may influence the hydrograph shape, such as AREA, URBEXT, DRAIND and MSL. The distance between the subject site and the potential Pivotal Stations was also taken into account, with local, hydrologically similar sites preferred over those situated further away.

Stations 35003 and 35005 have been discounted from further analysis due to low values of FARL (0.814 and 0.898 respectively) compared to that of the subject station, 0.986. These are due to the presence of numerous waterbodies in their upper catchments, such as Lough Arrow 20km upstream of Station 35003. As a result, peak flows are likely to experience some attenuation, slowing the response of the catchment to rainfall events and increasing the lag time of the hydrographs. This process is unlikely to occur at the subject station, 35002 and therefore these sites are deemed unrepresentative as Pivotal Stations. The remaining stations have been used as candidate Pivotal Stations for Billa Bridge and the resulting hydrographs have been plotted below:

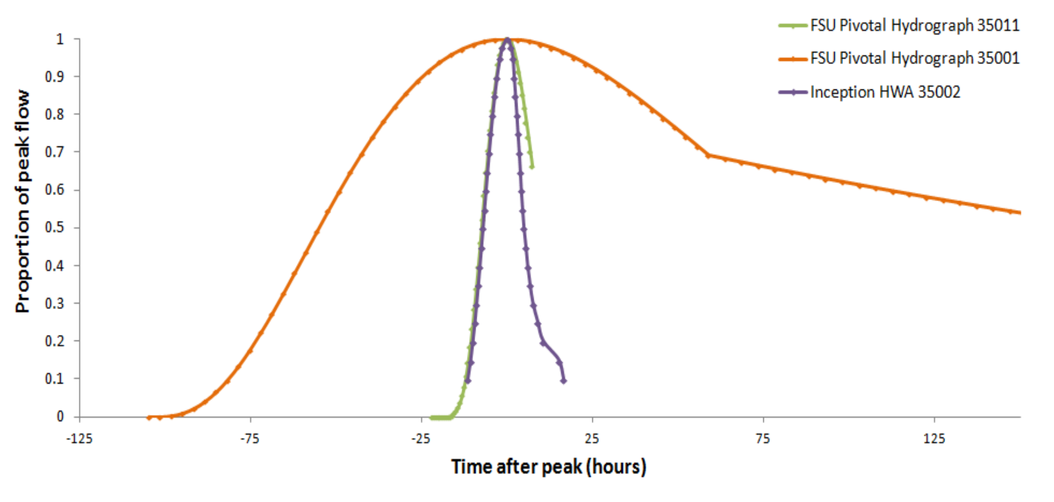


Figure E5-2: Comparison of FSU Pivotal Hydrographs derived from various Pivotal Stations with the Inception HWA hydrograph

Some of the catchment descriptors for sites 35001 and 35011 are similar to the subject site, with FARL values of 0.923 and 0.978 much closer to that at 35002, 0.986. Whilst both of the sites represent catchments that are slightly more urbanised than the subject catchment, the catchment descriptors MSL, DRAIND, SAAR, ALLUV and BFIsoil are similar between these three sites. However, the indices representing catchment area and slope are less comparable to the site of interest:

Catchment Descriptor	**Billa Bridge (35002)**	**Ballynacarrow (35001)**	**Dromahair (35011)**
AREA (km^2)	88.8	299.5	293.2
S1085 (m/km)	13.3	0.1	4.1

The larger area and shallow slope of the catchment area upstream of station 35001 is likely to contribute to the slow response to rainfall events, causing the wider hydrograph depicted in Figure E5-2. At station 35011, the steeper slope, combined with a higher value of ARTDRAIN, 4.78%, may route flows relatively quickly through the catchment, offsetting the large catchment area. The FSU Pivotal hydrograph, incorporating data from Station 35011, sufficiently replicates the fast response on both the rising limb and first 7 hours after the peak flow. The steep nature of this hydrograph is aided by the high gradient and arterial drainage of the Pivotal station, whilst the hydrograph derived from Station 35001, illustrates the effect of using an unrepresentative large, shallow gradient catchment as a Pivotal Station.

Recommendations

It is therefore recommended that the FSU Pivotal hydrograph, derived using station 35011, is the most representative of the Inception HWA observed flows at this location. Whilst it may slightly overestimate the time it takes for the catchment to return to natural flows after the peak event, it has the best fit to both the rising and initial falling limbs of the Inception HWA hydrograph in comparison to the hydrographs derived using alternative methods. If this hydrograph were to be incorporated into the hydraulic models, a more detailed investigation into the derivation of a recession limb would be required. The FSR Rainfall-Runoff derived hydrograph, whilst describing a more responsive catchment than that observed, has an acceptable fit and could be utilised if the FSR method was preferred regionally. The FSU Ungauged Hydrograph should not be used at this site as it exaggerates the length of time it takes for this catchment to respond to a rainfall event.

Ungauged Site Grid Reference 152472 229990			Clarinbridge @ Athenry		
Parameters					
FSR Rainfall - Runoff	Tp(0) (hours)	7.87	FSU (Ungauged)	T_r	50.03
				C	42.48
				n	6.54
	Storm Duration (hours)	16.6	FSU (Pivotal site 26022)	T_r	53.64
				C	66.94
				n	5.00

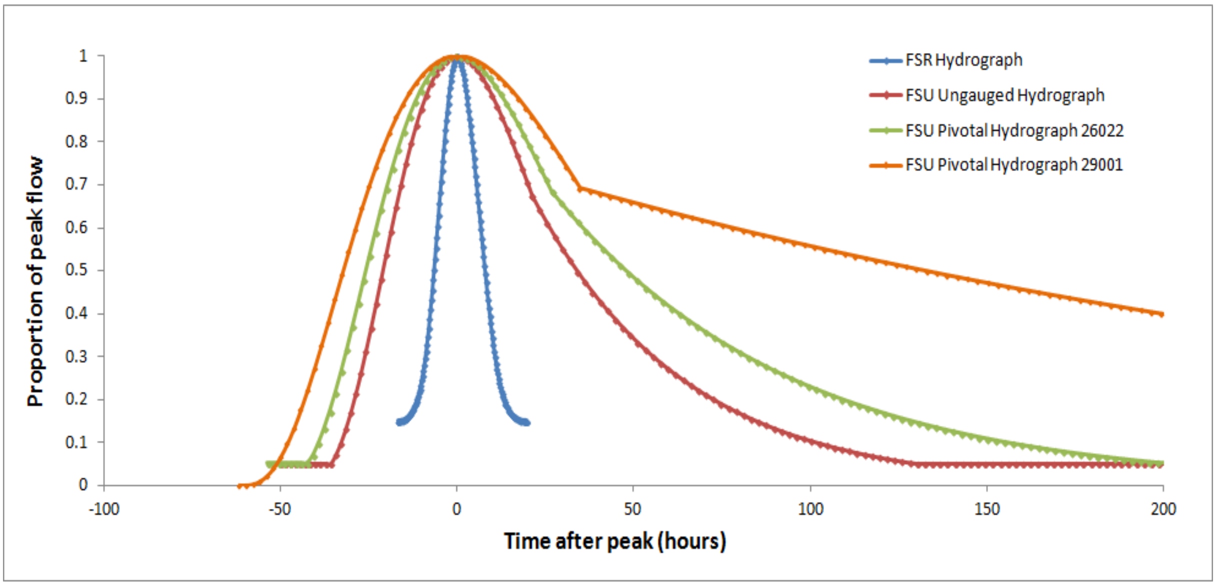


Figure E6-1: Comparison of hydrographs derived using the FSR-Rainfall Runoff and FSU methodologies

Review of Hydrograph Derivation and Shape

This ungauged site was not included in the Inception Hydrograph Width Analysis (HWA) and therefore there is no comparison between the derived hydrographs and the expected shape as with the gauged locations. This analysis focuses on the differences in hydrograph shape between the various methods tested.

FSR Rainfall-Runoff: This method produced a hydrograph with steep rising and falling limbs compared to the FSU methods, with a time to peak of approximately 17 hours. The near-symmetrical limbs do not account for the longer time taken for the channel to return to natural flows than its initial rapid response to rainfall.

FSU Ungauged: The hydrograph derived using this method estimates a slower catchment response than the FSR Rainfall-Runoff method, with the peak flow occurring approximately 37 hours into the event.

FSU Pivotal: The Pivotal Station 26022 was chosen following a detailed review of the gauges in Units of Management 29 and 26 and sites suggested by the Hydrograph Shape Generator (version 3) software supplied by OPW. The catchment descriptors at the local gauging stations Rathgorgin

(29001) and Craughwell (29007) in addition to Kilmore (26022) and the software chosen Sunville (25005) were reviewed for their similarity with the ungauged site at Athenry. Those used in the derivation of T_r, C and n parameters were checked for similarity to the subject site, in addition to other characteristics which may influence the hydrograph shape, such as AREA, URBEXT, DRAIND and MSL. The distance between the subject site and the candidate Pivotal Stations was also taken into account, with local, hydrologically similar sites preferred over those situated further away. Station 29007 has been excluded from further analysis given the large differences between key catchment descriptors at Craughwell and the subject site. Of particular note are the parameters MSL, ARTDRAIN, FARL, URBEXT and ALLUV, which are unrepresentative of the catchment upstream of Athenry. FARL, for example, at 0.969, implies a degree of attenuation which is not reflected in the value of 1.000 at Athenry, whilst the catchment at Craughwell is partially urbanised (URBEXT of 1.29%) compared to the rural catchment at the subject location. The station 29007 does provide similar descriptors for DRAIND, SAAR, S1085 and BFIsoil however these do not outweigh the number of parameters that make the site unsuitable for use as a Pivotal Station. The software chosen site, 25005, is less urbanised than Craughwell (URBEXT is 0.65 at Sunville) and has a more representative value for FARL (0.999). It however still performs poorly with respect to MSL, ARTDRAIN and ALLUV, the latter two of which influence the T_r parameter. This gauged location is also significantly larger than the subject site (193km^2 compared to 32km^2) and therefore it is likely that alternative stations offer more suitable catchments for use in Pivotal adjustments. This station has therefore been removed from further analysis. The catchments upstream of stations 29001 and 26022 have descriptors that are more consistent with those at Athenry compared to stations 29007 and 25005. The FSU Pivotal hydrographs have been plotted for each of these sites in Figure E6-1. The values of DRAIND, URBEXT and ALLUV are more similar to those of the subject site than the catchment descriptors from the other gauging stations (1.039, 0.66 and 2.29 respectively), whilst S1085, FARL, BFIsoil and SAAR are comparable between station 29001 and Athenry. However, the parameters for MSL and ARTDRAIN are not a good fit to those at the subject site. The ARTDRAIN value of 0.01 compared to 1.03 at Athenry suggests that the T_r parameter will vary between the two sites, influencing the shape of both the rising and falling limbs. It is likely that this parameter contributes to the slower response time of the hydrograph in Figure E6-1 and therefore it is suggested that station 29001 is not used as a Pivotal site for Athenry. Station 26022 offers a better fit to the catchment descriptors at Athenry for the majority of parameters, including URBEXT, ALLUV, MSL and FARL. ARTDRAIN remains low at 0.04 but improves upon the value of 0.01 at station 29001. Whilst the values of BFIsoil, SAAR, S1085 and DRAIND are less similar to those at the subject site than station 29001, they remain within a suitable range for use of Station 26022 as a Pivotal site. These values result in a hydrograph which represents a more responsive catchment than station 29001, as shown in Figure E6-1.
Recommendations
The various versions of the FSU hydrograph are all considerably wider than the FSR hydrograph. Without any observed data it is not possible to give a definitive recommendation on which is the most realistic design hydrograph shape. Further comparisons are described in the main text of the report.

Design Hydrograph analysis summary sheet

Ungauged Site **Grid Reference 166343 315264**			**Carrigans Upper @ Ballymote**		
Parameters					
FSR Rainfall - Runoff	Tp(0) (hours)	3.08	FSU (Ungauged)	T_r	56.31
				C	49.78
				n	6.26
	Storm Duration (hours)	6.67	FSU (Pivotal site 26022)	T_r	41.65
				C	51.98
				n	5.00

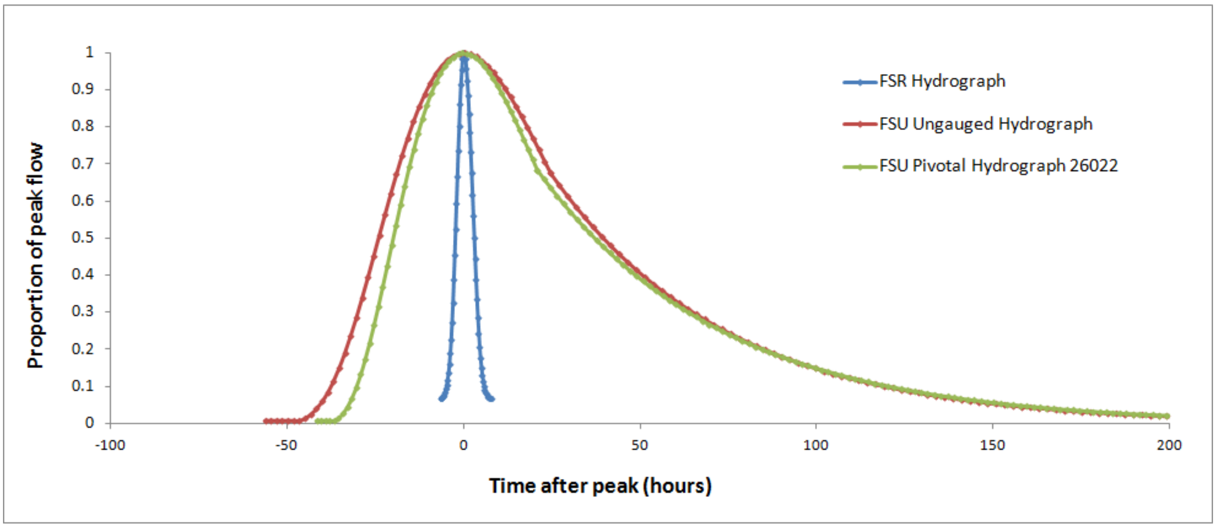


Figure E7-1: Comparison of hydrographs derived using the FSR-Rainfall Runoff and FSU methodologies

Review of Hydrograph Derivation and Shape

This ungauged site was not included in the Inception Hydrograph Width Analysis (HWA) and therefore there is no comparison between the derived hydrographs and the expected shape as with the gauged locations. This analysis focuses on the differences in hydrograph shape between the various methods tested.

FSR Rainfall-Runoff: This method produced a hydrograph with particularly steep rising and falling limbs in comparison with the FSU hydrographs. Its symmetrical shape does not take into account the change in catchment response throughout the event and different rates at which flow pathways transport water to the channel, which would result in a steep rising limb and shallow falling limb as seen in the FSU hydrographs. However, given the catchment size of 2.5km^2, the hydrograph's representation of a short-lived flood event reflects the small drainage area.

FSU Ungauged: The hydrograph derived using the FSU ungauged methodology describes a slowly responding catchment in comparison to the FSR Rainfall-Runoff method, with the peak flow occurring at approximately 50 hours into the event. It is highly unlikely that a catchment of this size would support a flood for this duration, therefore this method is believed to be unsuitable at Ballymote.

FSU Pivotal: The FSU Pivotal hydrograph also represents a slowly responding catchment, which is unlikely given the size and urban extent of the catchment. The process of choosing the Pivotal Station 26022 is detailed below.

The Pivotal Station 26022 was chosen following a detailed review of the gauges within Units of Management 35 and 26 and sites suggested by the Hydrograph Shape Generator (version 3) software supplied by OPW. The catchment descriptors at the gauging stations Ballynacarrow (35001), Kilmore (26022) and the software chosen Sunville (25005) were reviewed for their similarity with the ungauged site at Ballymote. Those used in the derivation of T_r, C and n parameters were checked for similarity to the subject site, in addition to other characteristics which may influence the hydrograph shape, such as AREA, URBEXT, DRAIND and MSL. The distance between the subject site and the candidate Pivotal Stations was also taken into account, with local, hydrologically similar sites preferred over those situated further away.

Station 35001 has been discounted from further analysis due to the large differences between key catchment characteristics at Ballynacarrow and Ballymote. Of particular note are the parameters AREA (299km^2 at Station 35001 compared to 2.5km^2 at the subject site), MSL (24.7km at Ballynacarrow compared to 2.2km at Ballymote) and URBEXT (0.33 at Station 35001 compared to 14.57 at Ballymote). In addition, S1085, which influences the T_r parameter, various from 0.1 at the candidate pivotal station to 2.6 at the subject site. More suitable values are present for DRAIND, FARL, SAAR, ALLUV and BFIsoil, however these do not outweigh the number of descriptors that make Ballynacarrow unsuitable for use as a Pivotal Station.

The software chosen station, 25005, represents a catchment with a similar degree of attenuation to Ballymote (FARL is 0.999 and 1.000 respectively). It also has comparable parameters for BFIsoil, SAAR, DRAIND and S1085, which influence the T_r, C and n parameters of the hydrograph shape. However, the disparity between the AREA, ALLUV, MSL, URBEXT and ARTDRAIN parameters at the two sites is also likely to be reflected in the hydrograph shape.

Catchment Descriptor	**Ballymote**	**Sunville (25005)**
AREA (km^2)	2.5	192.6
ALLUV (%)	0.00	7.99
MSL (km)	2.2	25.0
URBEXT (%)	14.57	0.65
ARTDRAIN (%)	0.00	8.97

This site has therefore not been plotted in Figure E7-1, as it is not considered suitable for use as a Pivotal station.

The catchment upstream of Station 26022 is described by parameters that improve upon those at stations 35001 and 25005. As for the software derived station, the catchment descriptors BFIsoil, SAAR and S1085 are similar to those at Ballymote, whilst AREA and MSL remain significantly different (61.9km^2 and 13.9km^2 respectively). However, Station 26022 improves upon the parameters at Station 25005 for ALLUV (1.27) and ARTDRAIN (0.04), influencing the T_r parameter. Despite this, the hydrograph shape depicted in Figure E7-1 indicates the FSU Pivotal method is not taking account of the small catchment area at Ballymote, resulting in an unrealistic duration for the hydrograph. Use of the FSU Pivotal method, with Station 26022 as the most representative pivotal station, should therefore not be used to estimate the hydrograph at Ballymote.

Recommendations

The various versions of the FSU hydrograph are extremely wide in comparison with the FSR hydrograph and they are considered unrepresentative of the expected flood duration on this very small

catchment. The FSR hydrograph is more realistic. Further tests of the hydrographs can be found in the main text of the report.

Ungauged Site **Grid Reference 144139 246625**	**Grange @ Corrofin**				
Parameters					
FSR Rainfall - Runoff	Tp(0) (hours)	12.15	FSU (Ungauged)	T_r	28.24
				C	45.80
				n	6.36
	Storm Duration (hours)	25.24	FSU (Pivotal site)	T_r	39.70
				C	8.31
				n	9.10

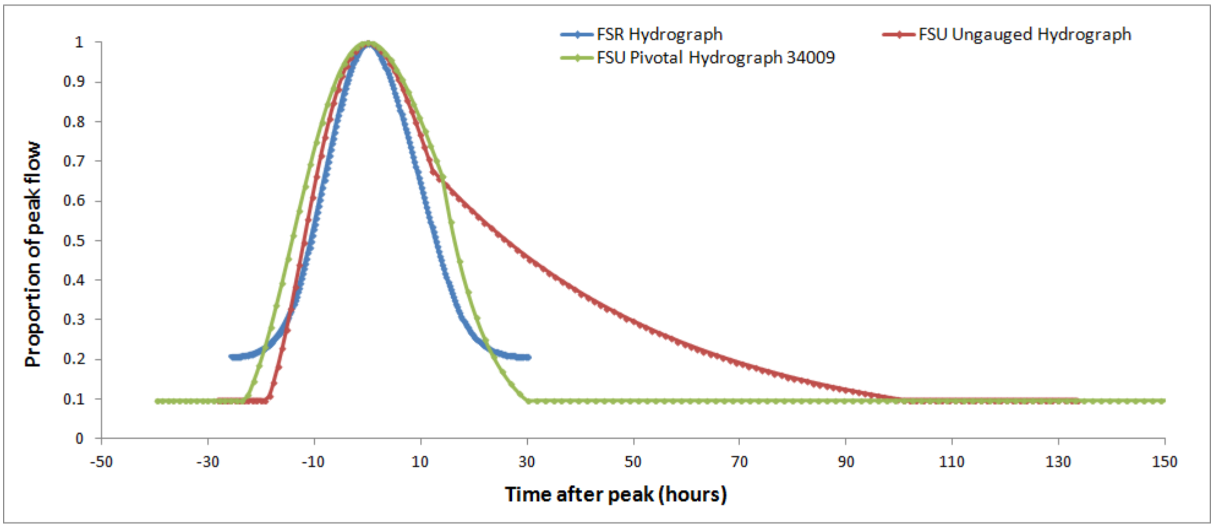


Figure E8-1: Comparison of hydrographs derived using the FSR-Rainfall Runoff and FSU methodologies

Review of Hydrograph Derivation and Shape

This ungauged site was not included in the Inception Hydrograph Width Analysis (HWA) and therefore there is no comparison between the derived hydrographs and the expected shape as with the gauged locations. This analysis focuses on the differences in hydrograph shape between the various methods tested.

FSR Rainfall-Runoff: This method produced a hydrograph with rising and falling limbs of a similar gradient to the FSU methods, with a time to peak of approximately 12 hours. Whilst comparable in shape, it does not account for the asymmetry expected in flood hydrographs which results from the catchment taking longer to return to natural flows than the time taken for peak flows to be reached in its response to rainfall.

FSU Ungauged: The hydrograph derived using this method estimates a comparable rising limb and initial falling limb to those from the FSR Rainfall-Runoff method. However, 12 hours after the peak flow, the falling limb decreases at a shallower gradient, implying a large proportion of the flow is from throughflow. This may be unrealistic given the catchment is not particularly permeable (BFIsoil is 0.571) and there is a high degree of arterial drainage works routing flows to the Grange River (ARTDRAIN is 18.1%).

FSU Pivotal: The Pivotal Station 34009 was chosen following a thorough review of the gauges in Units of Management 30 and 34 and sites suggested by the Hydrograph Shape Generator (version 3) software supplied by OPW. The catchment descriptors at the local gauging stations Ballygaddy (30007) and Clare (30012) in addition to Curraghbonaun (34009) and the software chosen Boleany (11001) were reviewed for their similarity with the ungauged site at Corrofin. Those used in the derivation of T_r, C and n parameters were checked for similarity to the subject site, in addition to other characteristics which may influence the hydrograph shape, such as AREA, URBEXT, DRAIND and MSL. The distance between the subject site and the candidate Pivotal Stations was also taken into account, with local, hydrologically similar sites preferred over those situated further away.

The software chosen site, 11001, has been excluded from further analysis given the disparity between two key catchment descriptors at Boleany compared to Corrofin. The differences in ARTDRAIN (6.3% compared to 18.05% at the subject site) and ALLUV (4.60% compared to 1.02% at the subject site) are much greater than at the local sites 30007 and 30012. Whilst some of the remaining descriptors, including AREA and S1085, are more comparable to those at Corrofin, ARTDRAIN and ALLUV are likely to alter the hydrograph shape through the T_r parameter. The remaining stations have more comparable values for these parameters and are therefore likely to act as more suitable Pivotal stations.

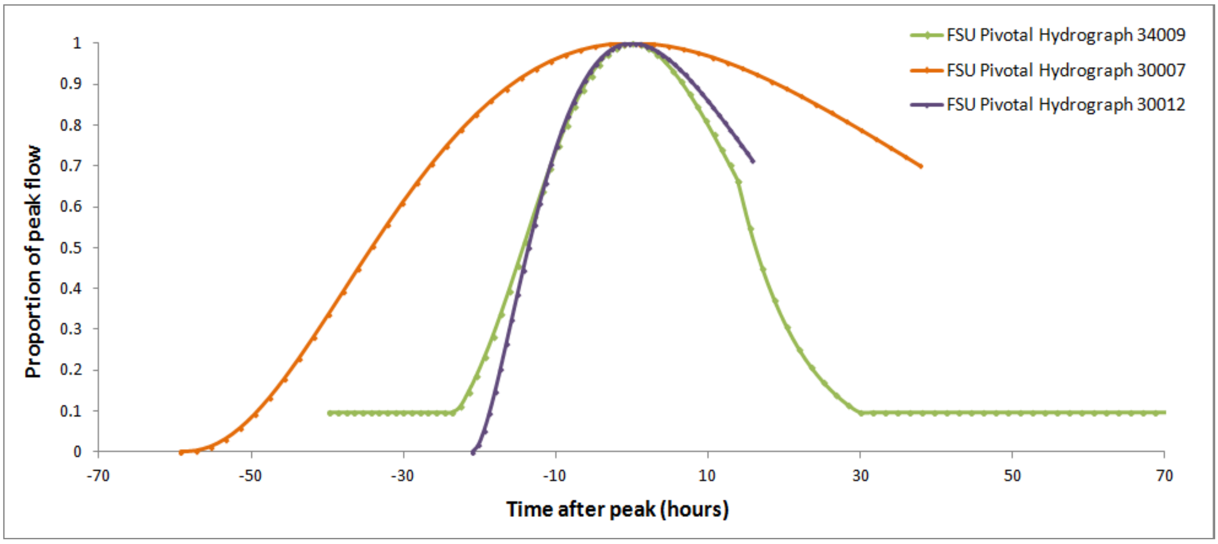


Figure E8-2: Comparison of FSU Pivotal Hydrographs derived from various Pivotal Stations

The FSU Pivotal hydrographs have been plotted for these three stations in Figure E8-2. It is clear that using station 30007 as a Pivotal site results in a hydrograph with a longer response time – it takes 55 hours for the hydrograph to reach peak flows compared to 20-25 hours when stations 30012 or 34009 are utilised. This extended response may be explained by the 470km^2 catchment at Ballygaddy, combined with the slightly more permeable soils and attenuation. These characteristics appear to outweigh the steeper slope and greater urban extent in catchment 30007 compared to the catchment upstream of site 30012, which is also large (1073km^2) yet produces a relatively narrow hydrograph. Given the disparity between the hydrograph based on station 30007, the alternative FSU hydrographs and the FSR Rainfall-Runoff method, it is suggested that this site is not used as a Pivotal station for Corrofin.

The majority of catchment descriptors for Station 30012 are comparable to those at Corrofin, with ARTDRAIN, FARL, BFIsoil and ALLUV providing similar parameters to the subject site. The hydrograph shape reflects this, with both the rising limb and initial falling limb having similar gradients to the FSU Ungauged and FSR Rainfall-Runoff hydrographs. However, the disparity between AREA (1073km^2 compared to 125.3km^2 at Corrofin) suggests the flow pathways are likely to be substantially

different between these two catchments despite the similarity in hydrograph shape. If no other sites could be utilised as a Pivotal station Clare could be used with caution, however given station 34009 remains a viable option, station 30012 is not likely to be used as the Pivotal station for Corrofin. Station 34009, Curraghbonaun, offers a better fit to the catchment descriptors at the subject site. Of particular note are the similarities in AREA, MSL, DRAIND, FARL, ALLUV and URBEXT, whilst BFIsoil, and S1095 still offer suitable values. ARTDRAIN, at 5.73%, is less comparable to the subject site than at stations 30007 and 30012. However, a degree of drainage is accounted for, and, given the remaining descriptors that contribute to the T_r parameter are consistent with those at Corrofin, it is likely that the predicted hydrograph shape is representative of the subject site. Whilst the centroid of this catchment is approximately 52km from that of the subject site, the above review of more local gauging stations suggests that station 34009, despite not being the closest to the subject catchment, is the most hydrologically similar.
Recommendations
It is therefore recommended that the FSU Pivotal hydrograph, derived using station 34009, is the most representative of the flows at this location. The rising and falling limbs appear to replicate the expected response to a rainfall event given the natural catchment topography and additional arterial drainage. If the FSU Ungauged method were preferred regionally, the hydrograph provides a reasonable representation of the catchment flows for the rising and initial falling limb, however the volume of flow is likely to be misrepresented given the delayed return to natural conditions. If the FSR Rainfall-Runoff method were utilised regionally, it could be used at Corrofin as it has a similar hydrograph shape to the FSU methods. At this ungauged site however, observed data is not available to support this conclusion. Further tests of the hydrographs can be found in the main text of the report.

Ungauged Site Grid Reference 162244 216389			St Clerans South @ Lough Rea		
Parameters					
FSR Rainfall - Runoff	Tp(0) (hours)	3.81	FSU (Ungauged)	T_r	61.72
				C	3087.17
				n	1.20
	Storm Duration (hours)	8.14	FSU (Pivotal site 34018)	T_r	32.05
				C	169.23
				n	1.27

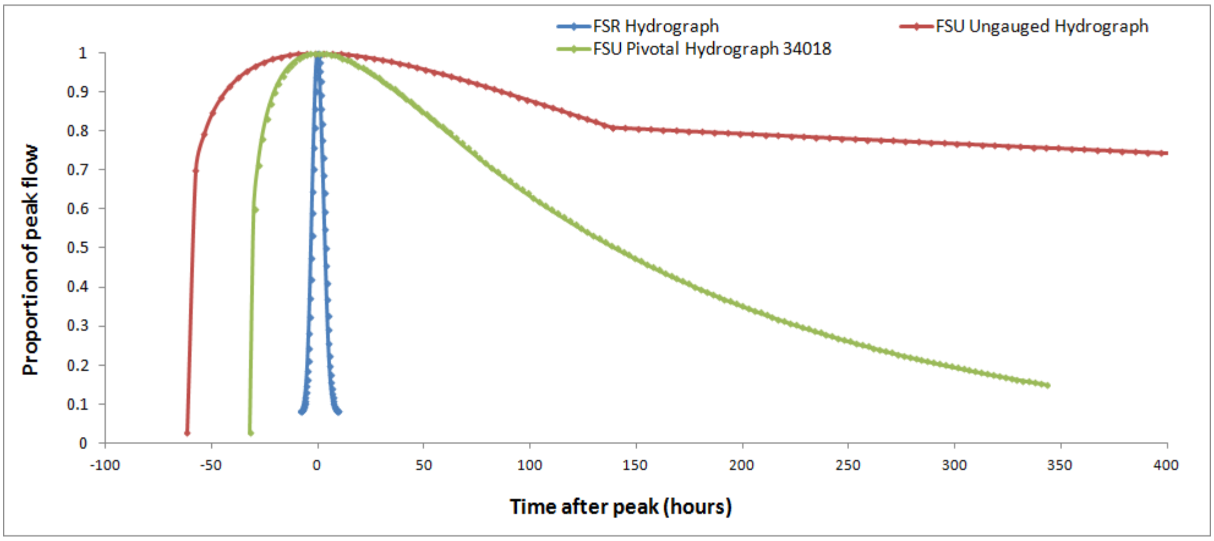


Figure E9-1: Comparison of hydrographs derived using the FSR-Rainfall Runoff and FSU methodologies

Review of Hydrograph Derivation and Shape

This site was not included in the Inception Hydrograph Width Analysis (HWA) and therefore there is no comparison between the derived hydrographs and the expected shape as with the locations for which flow data is available. This analysis focuses on the differences in hydrograph shape between the various methods tested.

FSR Rainfall-Runoff: This method produced a hydrograph with very steep rising and falling limbs compared to the FSU methods, with a time to peak of approximately 4 hours. Whilst the catchment is small (12.0 km^2), a large proportion of the catchment consists of Lough Rea, reducing the value of FARL to 0.499. This degree of attenuation is unlikely to be reflected in the quickly responding hydrograph produced by the FSR Rainfall-Runoff method. In addition, the symmetrical nature of the hydrograph does not account for the greater time taken for the channel to return to natural flows compared to the initial response to rainfall.

FSU Ungauged: The hydrograph estimated using this method describes a much slower catchment response than the FSR Rainfall-Runoff method, with the peak flow occurring approximately 60 hours into the event. Given the large degree of attenuation afforded by Lough Rea, this delayed response is a likely characteristic of the catchment during a flood event. However, the falling limb of this hydrograph is suspect given the large amount of time anticipated for the flows to return to natural levels. The low value for FARL (0.499) makes this exponential curve particularly shallow, however

given the catchment size, it is unlikely that such flows could be maintained at this level. This hydrograph is therefore unlikely to represent the complex hydrology at Lough Rea.

FSU Pivotal: The Pivotal Station 22071 was chosen following a thorough review of the gauges in Units of Management 29 and 34 and sites suggested by the Hydrograph Shape Generator (version 3) software supplied by OPW. The catchment descriptors at the local gauging stations Rathgorgin (29001), Turlough (34018) and the software chosen Lough Leane (22071) were reviewed for their similarity with the ungauged site at Lough Rea. Those used in the derivation of T_r, C and n parameters were checked for similarity to the subject site, in addition to other characteristics which may influence the hydrograph shape, such as AREA, URBEXT, DRAIND and MSL. The distance between the subject site and the candidate Pivotal Stations was also taken into account, with local, hydrologically similar sites preferred over those situated further away. However, given the unusual nature of the catchment, with a large degree of attenuation within a small, relatively steep, upland area, it is anticipated that a compromise will need to be made in finding the most hydrologically representative catchment for use as a Pivotal station.

Station 29001 has been excluded from further analysis given the large differences between key catchment descriptors at Rathgorgin and Lough Rea. Suitable descriptors include ARTDRAIN, SAAR and BFIsoil, however there are significant differences between all the remaining parameters, with FARL and S1085 in particular not representing the topography and attenuation in the Lough Rea catchment. A sample of these parameters is summarised below:

Catchment Descriptor	Lough Rea	Rathgorgin (29001)
ARTDRAIN (%)	0.00	0.01
SAAR	1134	1090
BFIsoil	0.727	0.581
FARL	0.499	0.998
S1085	6.85	2.22
URBEXT (%)	5.78	0.66

The catchment at Rathgorgin is therefore likely to be a poor representation of that at Lough Rea, such that the data should not be used to create a FSU Pivotal hydrograph at this site.

The software chosen site, 22071, improves upon the parameters for ARTDRAIN, S1085, FARL and BFIsoil at station 29001. The values at station 22071 are 0.00%, 7.76m/km, 0.730 and 0.638 respectively, better representing the rate at which water is routed through the catchment. However, the catchment area, rainfall and urban extent are not well represented by station 22071. This station has therefore been discounted in favour of station 34018 which has a more comparable set of descriptors for deriving the hydrograph shape parameters.

The FSU hydrograph, utilising station 34018 as a Pivotal station, has been plotted in Figure E9-1. Station 34018, whilst still relatively large at 95.4km^2, is smaller than the other options for a Pivotal station and has more comparable rainfall statistics to Lough Rea. The catchment upstream of Turlough is also described by an URBEXT value of 5.53 (compared to 5.78 at Lough Rea) and a BFIsoil value of 0.750 (0.727 at the subject site). However, the shallower gradient and increased arterial drainage in the catchment for station 34018 may cause the flows to respond differently between the candidate Pivotal station and the subject site. The method appears to produce a realistic hydrograph shape, with a steep rising limb due to the small catchment area followed by a delayed response due to attenuation of flows by upstream waterbodies. Whilst the falling limb is more realistic

than the FSU Ungauged hydrograph, it is still unlikely that a small catchment, such as Lough Rea, is able to produce floods of up to 350 hours duration, as illustrated in Figure E9-1.
Recommendations
The planned approach for flood estimation at Loughrea is the FSR rainfall-runoff method, with flood hydrographs routed through the lough using the hydraulic model. The FSR hydrograph shown above does not include flood routing, hence the short flood duration. The FSU hydrographs are very much more prolonged and produce a flood duration which is probably unrealistic given the small size of the catchment. Further tests of the hydrographs can be found in the main text of the report.

Design Hydrograph analysis summary sheet

Ungauged Site **Grid Reference 138637 299815**			**Swinford @ Swinford**		
Parameters					
FSR Rainfall - Runoff	Tp(0) (hours)	5.42	FSU (Ungauged)	T_r	22.39
				C	30.70
				n	6.08
	Storm Duration (hours)	12.17	FSU (Pivotal site 27001)	T_r	17.72
				C	11.24
				n	5.00

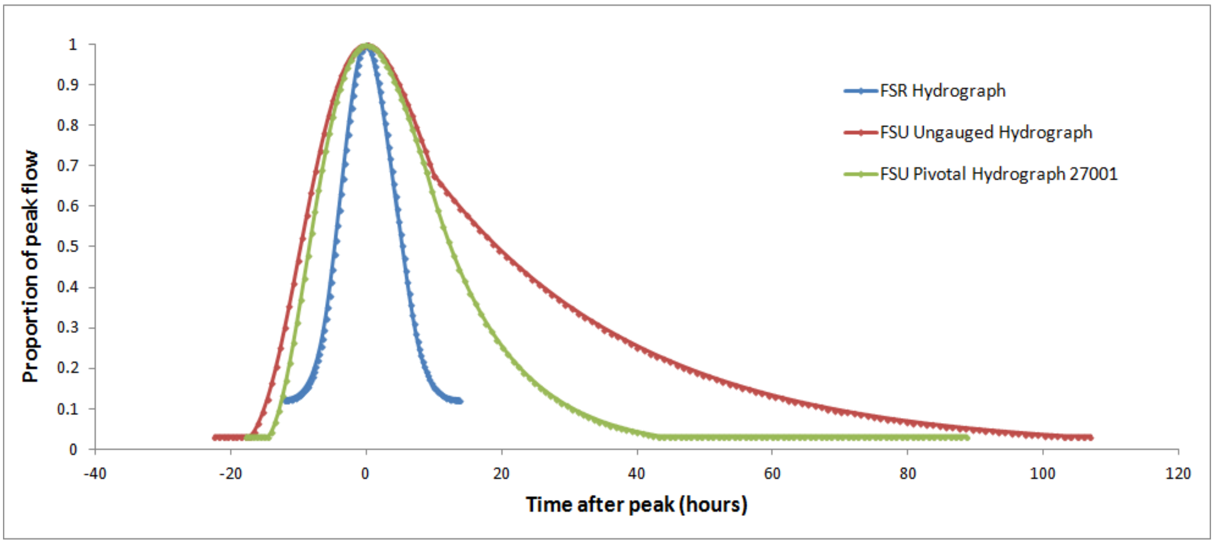


Figure E10-1: Comparison of hydrographs derived using the FSR-Rainfall Runoff and FSU methodologies

Review of Hydrograph Derivation and Shape

This ungauged site was not included in the Inception Hydrograph Width Analysis (HWA) and therefore there is no comparison between the derived hydrographs and the expected shape as with the gauged locations. This analysis focuses on the differences in hydrograph shape between the various methods tested.

FSR Rainfall-Runoff: This method produced a hydrograph with both rising and initial falling limbs that are steeper than the FSU hydrographs. It shows little sign of the asymmetry expected in flood hydrographs, with the catchment taking longer to return to natural flows than the time taken for peak flows to be reached in its response to a rainfall event.

FSU Ungauged: The hydrograph derived using this method appears to estimate a slower response of the catchment than the FSR Rainfall-Runoff method, with the peak flow being met approximately 17 hours into the event. This may be explained by attenuation in the catchment, with a FARL value of 0.933 increasing the response time of both the rising and falling limbs.

FSU Pivotal: The Pivotal Station 27001 was chosen following a detailed review of the gauges within Units of Management 34 and 30 and sites suggested by the Hydrograph Shape Generator (version 3) software supplied by OPW. The catchment descriptors at the local gauging stations Charlestown (34031), Curraghbonaun (34009), Ballyhaunis (30020), Turlough (34018) and Foxford (34003), in addition to Inch Bridge (27001) and the software chosen Aughnagross (16005) were reviewed for their

similarity with the ungauged site at Swinford. Those used in the derivation of T_r, C and n parameters were checked for similarity to the subject site, in addition to other characteristics which may influence the hydrograph shape, such as AREA, URBEXT, DRAIND and MSL. The distance between the subject site and the candidate Pivotal Stations was also taken into account, with local, hydrologically similar sites preferred over those situated further away.

Station 34018 has been discounted from further analysis given the large disparities between key catchment descriptors at this site and the subject location. Of particular note are the high values of MSL (23.738km compared to 9.897 at Swinford) and BFIsoil (0.750 compared to 0.462 at the subject site) which indicate station 34018 represents a larger, shallow gradient catchment with more permeable soils than the subject catchment. These characteristics would be likely to delay the response of the catchment to a rainfall event, increasing the time to peak of the flood hydrograph, which is not anticipated at the subject site. The remaining catchment descriptors are also unrepresentative of the catchment upstream of Swinford, ruling this site out for use as a Pivotal station.

Station 34003 also represents a catchment that is dissimilar to that upstream of Swinford. Whilst the indices for DRAIND and URBEXT are similar to those of the subject site, the values of 69.18km for MSL, 0.747 for BFIsoil and 0.961 for S1085 indicate this catchment is more similar to Station 34018 than the subject site. The catchment descriptor FARL also indicates a large degree of attenuation (FARL is 0.817 compared to 0.933) which is likely to overestimate that observed at Swinford. This site has therefore been discounted from further analysis.

The software chosen site, 16005, also has relatively high values of MSL and BFIsoil compared to the subject site, however they are more realistic than Stations 34018 and 34003. However, this station does not account for the attenuation expected at Swinford, with FARL given as 1.000. The remaining descriptors, including DRAIND, S1085 and URBEXT are similar to those at the subject site, however the distance of 170km between the sites suggests the remaining stations may be more suitable, Station 16005 has thus been removed from further analysis.

The catchments upstream of Stations 34031, 34009, 27001 and 30020 have catchment descriptors that are more consistent with those of the subject site. Station 34031 has indices for MSL and BFIsoil of 9.102km and 0.329 respectively; however the catchment has no reservoir attenuation and is steeper than the subject catchment. Rainfall is therefore anticipated to be routed quickly through the catchment, resulting in a shorter time to peak in the event hydrograph. This can be seen in Figure E10-2 where using this site as a Pivotal Station gives the steepest hydrograph. Station 30020 also has representative descriptors for MSL and URBEXT, however the high percentage of ARTDRAIN (19.37% compared to 0% at the subject site), shallow slope of 2.891m/km and permeable soils (BFIsoil 0.610) result in a hydrograph with a relatively steep rising limb but a slow return back to baseflow conditions. Using station 34009 as a Pivotal Station results in a hydrograph with a delayed response to rainfall, as seen in Figure E10-2. This is likely to be due to the shallow gradient of the 117km^2 catchment (S1085 is 3.33m/km), which, despite arterial drainage, routes flows relatively slowly to the gauging station. The subject catchment is much smaller (13.2km^2) and steeper (S1085 is 6.83m/km) and therefore using Station 34009 to create a pivotal hydrograph is not recommended.

Station 27001, whilst outside the UoM, appears to give the best fit of catchment descriptors at Swinford. The catchment has a similar slope and drainage density to the subject site (S1085 is 4.448m/km compared to 6.83 at Swinford) and has no arterial drainage or urban development. BFIsoil is also similar at 0.330 whilst a value of 0.987 for FARL indicates some a degree of attenuation similar to that of the catchment upstream of Swinford. Use of this site as a Pivotal Station results in a hydrograph shape that is steeper than that of 34009, but accounts for more attenuation and a more delayed catchment response than 34031 and 30020.

The distance between the catchment centroids of Station 27001 and the 13km^2 catchment at Swinford is approximately 3.8km, much smaller than the distance between the subject site and stations within UoM 34. Whilst site 27001 is therefore not located in the same UoM as the subject site, its centroid is

nearby and its catchment is similar to that at Swinford. This gauged location is therefore deemed the most suitable site as a Pivotal Station for Swinford.

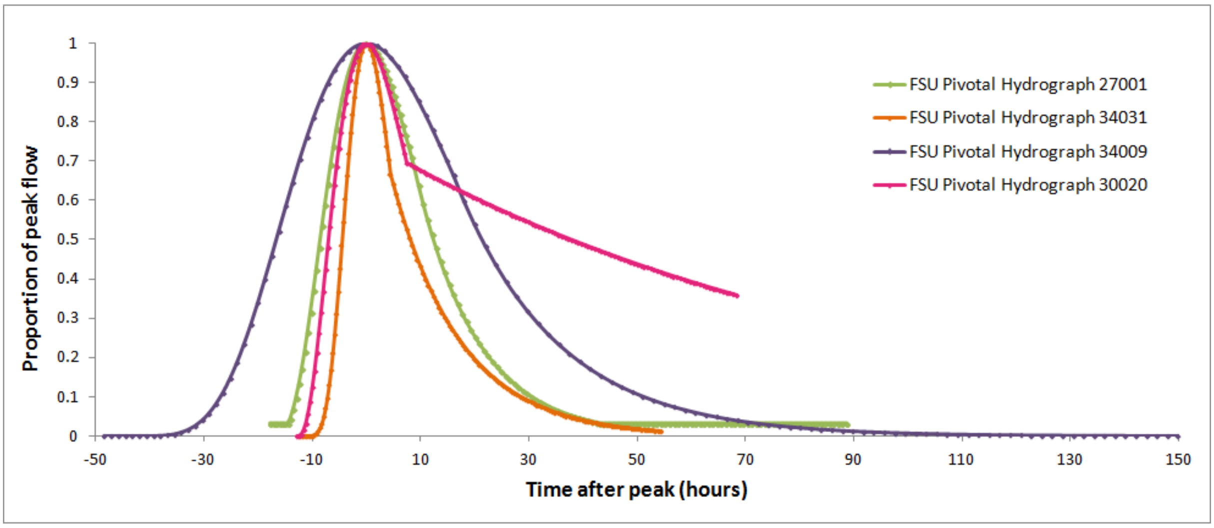


Figure E10-2: Comparison of FSU Pivotal Hydrographs derived from various Pivotal Stations

Recommendations

The various versions of the FSU hydrograph are rather wider than the FSR hydrograph. Without any observed data it is not possible to give a definitive recommendation on which is the most realistic design hydrograph shape. Further tests are described in the main text of the report.

F Design flows for each HEP

HEP label	FSU node	X	Y	QMED adjustment source (none if blank)	QMED adjustment (none if blank)	Growth curve		FSR Rainfall Runoff ratio applied to 1% AEP peak flow by AEP(%)		Peak Flow (m^3/s) by AEP(%)							
						Single-site /Pooled	Distribution	0.5	0.1	50	20	10	5	2	1	0.5	0.1
BGR_001	29_410_2	150064	227098			P	GL	1.18	1.76	0.99	1.30	1.51	1.74	2.08	2.37	2.79	4.19
BLH_001	29_602_1	144217	201771			P	GL	1.12	1.52	0.23	0.31	0.36	0.42	0.50	0.58	0.65	0.88
BLH_003	29_675_4	145159	202399			P	GL	1.16	1.68	0.34	0.44	0.51	0.58	0.70	0.79	0.92	1.33
BNG_001	29_300_1	140963	224692	Regional	1.00	P	GL	1.15	1.66	0.47	0.59	0.68	0.77	0.91	1.02	1.18	1.70
BNG_002	29_300_2	139916	225009	Regional	1.00	P	GL	1.16	1.68	0.76	0.97	1.11	1.26	1.48	1.67	1.94	2.81
BNG_003	29_300_6	138345	224477	Regional	1.00	P	GL	1.16	1.70	1.29	1.64	1.89	2.14	2.52	2.83	3.29	4.80
BNG_004	29_300_6	138325	224473	Regional	1.00	P	GL	1.16	1.70	1.65	2.09	2.40	2.73	3.21	3.61	4.19	6.13
BNG_005	29_300_7	138107	224945	Regional	1.00	P	GL	1.16	1.67	1.49	1.88	2.15	2.44	2.86	3.21	3.72	5.38
CLB_001	29_359_3	152472	229990	Regional	1.00	P	GEV	1.16	1.69	5.90	7.48	8.46	9.35	10.44	11.22	13.01	19.01
CLB_002	29_359_8	151131	228827	Regional	1.00	P	GEV	1.16	1.69	5.98	7.53	8.48	9.33	10.38	11.11	12.89	18.82
CLB_003	29_358_1	151103	228814	Regional	1.00	P	GEV	1.16	1.69	6.52	8.21	9.24	10.18	11.32	12.11	14.05	20.52
CLB_004	29_358_3	150574	228031	Regional	1.00	P	GEV	1.16	1.69	6.77	8.52	9.59	10.56	11.74	12.57	14.59	21.30
CLB_005	29_358_6	150042	227120	Regional	1.00	P	GEV	1.16	1.70	7.19	9.05	10.19	11.23	12.48	13.36	15.52	22.71
CLB_006	29_310_1	149995	227080	Regional	1.00	P	GEV	1.16	1.70	7.42	9.32	10.47	11.52	12.78	13.66	15.87	23.23
CLB_007	29_310_3	149270	226465	Regional	1.00	P	GEV	1.16	1.70	8.34	10.40	11.64	12.75	14.09	15.01	17.44	25.57
CLB_008	29_310_6	147898	224753	Regional	1.00	P	GEV	1.16	1.70	8.70	10.85	12.15	13.31	14.70	15.67	18.20	26.64
CLB_009	29_428_1	147804	224737	Regional	1.00	P	GEV	1.16	1.70	13.68	16.75	18.57	20.18	22.07	23.36	27.11	39.65
CLB_010	29_428_3	147300	224059	Regional	1.00	P	GEV	1.16	1.70	14.28	17.49	19.39	21.07	23.04	24.39	28.31	41.39
CLB_011	29_428_7	146523	222861	Regional	1.00	P	GEV	1.16	1.69	14.06	17.24	19.12	20.78	22.71	24.03	27.87	40.68
CLB_012	29_387_4	144480	222110	Regional	1.00	P	GEV	1.16	1.69	14.90	18.22	20.13	21.78	23.67	24.93	28.89	42.08
CLB_013	29_388_2	141610	220204	Regional	1.00	P	GEV	1.16	1.68	15.48	19.02	21.08	22.87	24.95	26.34	30.49	44.30
CLB_014	29_388_3	141087	220021	Regional	1.00	P	GEV	1.16	1.68	15.63	19.20	21.28	23.09	25.18	26.59	30.78	44.73
CNW_001	29_675_1	144876	201303			P	GL	1.11	1.48	17.53	21.18	23.56	25.92	29.18	31.80	35.44	47.08
CNW_002	29_675_3	145300	202017			P	GL	1.11	1.48	17.48	21.13	23.50	25.86	29.11	31.72	35.35	46.94
CNW_003	29_675_6	145799	203164			P	GL	1.11	1.48	17.80	21.51	23.93	26.33	29.63	32.29	35.99	47.79
CNW_004	29_675_9	145762	204026			P	GL	1.11	1.48	17.83	21.54	23.96	26.37	29.68	32.34	36.04	47.84
CNW2_001	29_675_1	144886	201226			P	GL	1.11	1.48	17.24	20.84	23.17	25.50	28.70	31.28	34.86	46.31
CWM_001	29_339_1	138891	225410	Regional	1.00	P	GL	1.16	1.69	0.70	0.88	1.01	1.14	1.33	1.49	1.73	2.52
CWM_002	29_339_1	138589	225237	Regional	1.00	P	GL	1.16	1.69	0.71	0.89	1.02	1.15	1.34	1.51	1.74	2.54
CWM_003	29_339_3	138118	224970	Regional	1.00	P	GL	1.17	1.72	1.48	1.85	2.12	2.39	2.80	3.14	3.66	5.42

HEP label	FSU node	X	Y	QMED adjustment source (none if blank)	QMED adjustment (none if blank)	Growth curve		FSR Rainfall Runoff ratio applied to 1% AEP peak flow by AEP(%)		Peak Flow (m^3/s) by AEP(%)							
						Single-site /Pooled	Distribution	0.5	0.1	50	20	10	5	2	1	0.5	0.1
CWM_004	29_132_1	138089	224970	Regional	1.00	P	GL	1.16	1.68	2.89	3.54	3.98	4.44	5.09	5.63	6.52	9.47
CWM_005	29_339_3	137972	224939	Regional	1.00	P	GL	1.17	1.72	2.44	3.01	3.40	3.80	4.37	4.85	5.66	8.37
CWM_006	29_132_2	137787	224856	Regional	1.00	P	GL	1.16	1.71	3.71	4.55	5.13	5.71	6.55	7.25	8.43	12.40
GOR_001	29_602_1	144505	200284			P	GL	1.12	1.52	0.13	0.17	0.20	0.23	0.28	0.32	0.36	0.49
GOR_002	29_602_1	144607	200670			P	GL	1.12	1.52	0.16	0.21	0.25	0.29	0.35	0.41	0.46	0.62
GOR_003	29_602_2	144780	200888			P	GL	1.12	1.51	0.26	0.34	0.40	0.47	0.57	0.65	0.73	0.98
GOR_004	29_674_2	144820	201226			P	GL	1.12	1.51	0.48	0.63	0.74	0.86	1.04	1.20	1.34	1.81
KLC_001	29_533_1	157501	219705	29007	0.84	SS	G	1.16	1.68	2.90	3.75	4.28	4.80	5.47	5.96	6.91	10.04
KLC_002	29_533_7	154960	220334	29007	0.84	SS	G	1.16	1.68	3.10	4.01	4.58	5.13	5.85	6.38	7.38	10.71
KLC_003	29_483_1	154840	220353	29007	0.84	SS	G	1.16	1.68	3.53	4.56	5.21	5.84	6.65	7.26	8.40	12.19
KLC_004	29_635_3	153733	220622	29007	0.84	SS	G	1.16	1.68	3.80	4.90	5.61	6.28	7.16	7.81	9.04	13.13
KLC_005	29_70_1	153656	220617	29007	0.84	SS	G	1.16	1.68	14.99	19.36	22.13	24.80	28.25	30.83	35.70	51.93
KLC_006	29_263_4	152112	220060	29007	0.84	SS	G	1.16	1.68	15.59	20.15	23.03	25.81	29.39	32.07	37.14	54.00
KLC_007	29_671_1	152075	220034	29007	0.84	SS	G	1.15	1.65	28.39	36.68	41.93	46.98	53.51	58.39	67.25	96.58
KLC_008	29_671_3	151006	219938	29007	0.84	SS	G	1.15	1.65	27.78	35.89	41.03	45.97	52.36	57.14	65.76	94.30
KLC_009	29_672_3	149188	219590	Weighted 29007 and 29011	0.74	SS	G	1.15	1.65	27.74	36.81	42.18	47.34	54.02	59.01	67.95	97.55
KLC_010	29_672_10	145992	218741	Weighted 29007 and 29011	0.72	SS	G	1.15	1.65	28.46	37.93	43.48	48.80	55.71	60.86	70.09	100.66
KLC_011	29_669_2	141809	218491	29011	0.70	SS	G	1.15	1.65	29.28	39.27	45.04	50.57	57.75	63.10	72.64	104.20
KNG_001	29_71_2	151126	228813			P	GL	1.17	1.76	0.70	0.92	1.08	1.24	1.49	1.71	2.00	3.00
MDF_001	29_300_6	137937	223797	Regional	1.00	P	GL	1.16	1.70	0.03	0.04	0.05	0.06	0.07	0.08	0.09	0.13
MDF_002	29_300_6	137806	223653	Regional	1.00	P	GL	1.16	1.70	0.04	0.05	0.06	0.07	0.08	0.09	0.11	0.16
MDF_003	29_300_6	137644	223616	Regional	1.00	P	GL	1.16	1.70	0.05	0.07	0.08	0.10	0.12	0.14	0.16	0.23
MLP_001	29_430_16	147860	224727			P	GL	1.16	1.71	4.64	5.81	6.60	7.40	8.54	9.49	11.04	16.21
RCK_001	29_300_5	138911	224017	Regional	1.00	P	GL	1.16	1.69	0.34	0.45	0.53	0.62	0.75	0.86	1.00	1.46
RCK_002	29_300_5	138354	224456	Regional	1.00	P	GL	1.16	1.69	0.38	0.50	0.59	0.68	0.83	0.96	1.11	1.62
RRD_004	29_497_3	161371	219096	29007	0.84	P	GL	1.17	1.76	0.12	0.16	0.19	0.22	0.27	0.31	0.36	0.54

HEP label	FSU node	X	Y	QMED adjustment source (none if blank)	QMED adjustment (none if blank)	Growth curve		FSR Rainfall Runoff ratio applied to 1% AEP peak flow by AEP(%)		Peak Flow (m^3/s) by AEP(%)							
						Single-site /Pooled	Distribution	0.5	0.1	50	20	10	5	2	1	0.5	0.1
SCL_001	29_519_1	161351	219169	29007	0.84	P	GL	1.16	1.68	1.30	1.63	1.86	2.10	2.43	2.71	3.14	4.56
SCL_002	29_519_5	159711	220083	29007	0.84	P	GL	1.16	1.68	1.52	1.91	2.18	2.45	2.85	3.17	3.67	5.33
SCL_003	29_519_10	157598	219711	29007	0.84	P	GL	1.16	1.68	1.87	2.35	2.67	2.99	3.46	3.84	4.45	6.45
SCLN_011	29_497_3	161424	219143			P	GL	1.17	1.76	1.14	1.49	1.75	2.03	2.45	2.82	3.31	4.96
SCLS_001	29_660_2	162222	216357	29007	0.84	P	GL	1.15	1.65	0.35	0.45	0.51	0.59	0.69	0.78	0.89	1.28
SCLS_002	29_661_5	162254	216411	29007	0.84	P	GL	1.17	1.72	2.97	3.76	4.32	4.91	5.77	6.50	7.58	11.15
SCLS_003	29_513_4	162256	217730	29007	0.84	P	GL	1.16	1.68	0.74	0.93	1.07	1.20	1.40	1.57	1.81	2.63
SCLS_004	29_513_9	161427	219095	29007	0.84	P	GL	1.16	1.67	0.84	1.06	1.21	1.37	1.60	1.78	2.06	2.99
TNR_001	29_661_1	163579	215841	29007	0.84	P	GL	1.18	1.78	0.03	0.04	0.05	0.06	0.07	0.08	0.09	0.14
TNR_002	29_661_2	163336	216126	29007	0.84	P	GL	1.21	1.89	0.47	0.62	0.73	0.85	1.04	1.19	1.44	2.25
TNR_003	29_661_3	162842	216195	29007	0.84	P	GL	1.19	1.82	0.54	0.72	0.85	0.99	1.20	1.38	1.64	2.52
TNR_004	29_661_4	162407	216281	29007	0.84	P	GL	1.19	1.82	0.65	0.86	1.02	1.19	1.44	1.66	1.97	3.01
TUL_012	29_117_5	157621	219680	29007	0.84	P	GL	1.17	1.72	1.59	2.01	2.31	2.62	3.08	3.47	4.04	5.95

Design flows given in the table above have been developed from the recommended design flows at gauging stations but these have been further modified in some areas through regional smoothing of the QMED adjustment factor. In addition, for all HEPs the flood growth curve was extended for AEPs lower than 1% using ratios from FSR rainfall-runoff method growth curves. Please refer to Appendix B Flood peak analysis for the preliminary recommended design flows at gauging stations prior to these additional modifications. A summary of the flood estimation process is given in Table 7-1 of the main report.

HEP label	Future peak flow - MRFS (m^3/s) by AEP(%)								Future peak flow - HEFS (m^3/s) by AEP(%)							
	50	20	10	5	2	1	0.5	0.1	50	20	10	5	2	1	0.5	0.1
BGR_001	1.21	1.58	1.84	2.12	2.53	2.89	3.39	5.10	1.32	1.72	2.01	2.31	2.76	3.15	3.70	5.56
BLH_001	0.28	0.37	0.43	0.50	0.61	0.70	0.78	1.06	0.30	0.40	0.47	0.54	0.66	0.75	0.85	1.15
BLH_003	0.41	0.53	0.61	0.70	0.84	0.95	1.10	1.60	0.45	0.57	0.67	0.76	0.91	1.03	1.19	1.73
BNG_001	0.56	0.71	0.82	0.93	1.09	1.23	1.42	2.04	0.61	0.77	0.88	1.00	1.18	1.33	1.53	2.21
BNG_002	0.92	1.16	1.33	1.52	1.78	2.01	2.32	3.38	0.99	1.26	1.45	1.64	1.93	2.17	2.52	3.66
BNG_003	1.56	1.97	2.27	2.57	3.02	3.41	3.95	5.78	1.69	2.14	2.46	2.79	3.28	3.69	4.29	6.26
BNG_004	1.98	2.52	2.89	3.28	3.85	4.34	5.04	7.36	2.15	2.73	3.13	3.56	4.18	4.71	5.47	7.98
BNG_005	1.79	2.26	2.59	2.94	3.44	3.87	4.48	6.48	1.95	2.46	2.82	3.19	3.74	4.21	4.86	7.03
CLB_001	7.08	8.98	10.15	11.22	12.53	13.46	15.62	22.81	7.67	9.72	11.00	12.16	13.58	14.58	16.92	24.71
CLB_002	7.18	9.03	10.17	11.20	12.45	13.33	15.46	22.58	7.77	9.78	11.02	12.13	13.49	14.44	16.75	24.46
CLB_003	7.83	9.85	11.09	12.22	13.58	14.54	16.86	24.63	8.48	10.67	12.02	13.23	14.71	15.75	18.27	26.68
CLB_004	8.14	10.25	11.54	12.71	14.13	15.13	17.55	25.64	8.84	11.12	12.52	13.79	15.33	16.41	19.04	27.82
CLB_005	8.70	10.95	12.33	13.58	15.09	16.15	18.76	27.46	9.46	11.90	13.40	14.76	16.41	17.57	20.40	29.86
CLB_006	8.98	11.27	12.67	13.94	15.46	16.53	19.20	28.11	9.76	12.26	13.78	15.16	16.82	17.98	20.89	30.58
CLB_007	10.09	12.58	14.09	15.43	17.05	18.16	21.11	30.95	10.98	13.69	15.33	16.79	18.55	19.76	22.97	33.67
CLB_008	10.53	13.13	14.70	16.11	17.79	18.95	22.02	32.23	11.45	14.28	15.99	17.52	19.35	20.62	23.95	35.06
CLB_009	16.52	20.22	22.42	24.36	26.64	28.20	32.73	47.87	17.95	21.97	24.36	26.47	28.95	30.64	35.57	52.01
CLB_010	17.24	21.11	23.40	25.42	27.81	29.43	34.17	49.95	18.73	22.93	25.42	27.62	30.21	31.98	37.12	54.26
CLB_011	16.97	20.80	23.07	25.07	27.40	28.99	33.63	49.07	18.43	22.60	25.06	27.23	29.77	31.50	36.53	53.31
CLB_012	17.96	21.96	24.27	26.25	28.53	30.05	34.82	50.72	19.51	23.85	26.35	28.50	30.98	32.63	37.81	55.07
CLB_013	18.66	22.92	25.40	27.56	30.06	31.74	36.74	53.38	20.25	24.88	27.58	29.92	32.63	34.46	39.89	57.95
CLB_014	18.83	23.13	25.64	27.82	30.34	32.04	37.09	53.90	20.44	25.11	27.84	30.20	32.94	34.78	40.26	58.52
CNW_001	21.03	25.42	28.27	31.11	35.01	38.16	42.53	56.49	22.78	27.54	30.63	33.70	37.93	41.34	46.08	61.20
CNW_002	21.00	25.38	28.23	31.06	34.96	38.10	42.46	56.38	22.76	27.51	30.59	33.66	37.89	41.29	46.02	61.11
CNW_003	21.40	25.86	28.76	31.65	35.62	38.82	43.26	57.44	23.20	28.04	31.19	34.31	38.62	42.09	46.91	62.28
CNW_004	21.43	25.90	28.80	31.69	35.67	38.87	43.32	57.50	23.23	28.08	31.23	34.36	38.68	42.15	46.97	62.35
CNW2_001	20.69	25.00	27.81	30.60	34.44	37.53	41.84	55.57	22.41	27.09	30.13	33.15	37.31	40.66	45.32	60.20
CWM_001	0.85	1.07	1.22	1.38	1.62	1.81	2.10	3.06	0.93	1.17	1.33	1.51	1.76	1.98	2.29	3.33
CWM_002	0.86	1.08	1.23	1.39	1.63	1.83	2.12	3.09	0.94	1.18	1.35	1.52	1.78	1.99	2.31	3.36
CWM_003	1.80	2.26	2.58	2.91	3.41	3.82	4.46	6.59	1.97	2.46	2.81	3.18	3.72	4.17	4.87	7.20
CWM_004	3.50	4.29	4.83	5.38	6.17	6.83	7.91	11.48	3.81	4.67	5.26	5.86	6.72	7.44	8.61	12.51
CWM_005	2.97	3.67	4.14	4.63	5.33	5.91	6.89	10.19	3.24	4.00	4.52	5.05	5.81	6.44	7.52	11.12
CWM_006	4.51	5.53	6.22	6.93	7.95	8.80	10.24	15.04	4.91	6.02	6.78	7.55	8.66	9.58	11.15	16.39

HEP label	Future peak flow - MRFS (m^3/s) by AEP(%)								Future peak flow - HEFS (m^3/s) by AEP(%)							
	50	20	10	5	2	1	0.5	0.1	50	20	10	5	2	1	0.5	0.1
GOR_001	0.15	0.20	0.24	0.27	0.33	0.38	0.43	0.58	0.16	0.22	0.25	0.30	0.36	0.42	0.47	0.63
GOR_002	0.20	0.26	0.30	0.35	0.43	0.49	0.55	0.74	0.21	0.28	0.33	0.38	0.46	0.53	0.60	0.81
GOR_003	0.31	0.41	0.48	0.56	0.68	0.78	0.88	1.18	0.33	0.44	0.52	0.61	0.73	0.85	0.95	1.28
GOR_004	0.58	0.76	0.89	1.03	1.25	1.43	1.61	2.17	0.62	0.82	0.96	1.12	1.35	1.55	1.74	2.35
KLC_001	3.54	4.58	5.23	5.86	6.68	7.28	8.43	12.26	3.87	5.00	5.72	6.40	7.30	7.96	9.22	13.40
KLC_002	3.78	4.89	5.59	6.26	7.13	7.78	9.00	13.06	4.13	5.34	6.10	6.84	7.79	8.50	9.83	14.26
KLC_003	4.30	5.55	6.35	7.11	8.10	8.84	10.23	14.85	4.69	6.06	6.93	7.76	8.84	9.65	11.16	16.20
KLC_004	4.62	5.97	6.83	7.65	8.71	9.51	11.00	15.99	5.04	6.51	7.45	8.34	9.50	10.37	12.01	17.45
KLC_005	18.08	23.36	26.70	29.92	34.07	37.18	43.06	62.64	19.63	25.37	29.00	32.49	37.01	40.39	46.77	68.04
KLC_006	18.81	24.30	27.78	31.13	35.45	38.69	44.80	65.13	20.43	26.39	30.17	33.81	38.50	42.02	48.65	70.74
KLC_007	34.19	44.17	50.50	56.58	64.45	70.33	80.99	116.32	37.11	47.94	54.81	61.41	69.94	76.33	87.90	126.24
KLC_008	33.46	43.23	49.42	55.37	63.07	68.82	79.21	113.58	36.31	46.92	53.63	60.10	68.45	74.70	85.97	123.28
KLC_009	33.41	44.33	50.80	57.01	65.05	71.06	81.82	117.47	36.25	48.11	55.13	61.87	70.60	77.12	88.80	127.49
KLC_010	34.26	45.67	52.35	58.76	67.07	73.28	84.39	121.20	37.18	49.56	56.81	63.77	72.78	79.52	91.58	131.52
KLC_011	35.25	47.27	54.21	60.88	69.51	75.96	87.44	125.43	38.25	51.29	58.82	66.05	75.42	82.42	94.87	136.09
KNG_001	0.84	1.10	1.29	1.49	1.79	2.05	2.40	3.60	0.91	1.20	1.40	1.61	1.94	2.22	2.60	3.90
MDF_001	0.04	0.05	0.06	0.07	0.08	0.09	0.11	0.16	0.04	0.05	0.06	0.07	0.09	0.10	0.12	0.17
MDF_002	0.04	0.06	0.07	0.08	0.10	0.11	0.13	0.19	0.05	0.06	0.07	0.09	0.10	0.12	0.14	0.21
MDF_003	0.07	0.09	0.10	0.12	0.14	0.17	0.19	0.28	0.07	0.09	0.11	0.13	0.16	0.18	0.21	0.30
MLP_001	5.59	6.99	7.94	8.91	10.28	11.42	13.28	19.50	6.06	7.58	8.61	9.66	11.15	12.39	14.41	21.15
RCK_001	0.41	0.54	0.64	0.74	0.90	1.03	1.20	1.75	0.44	0.59	0.69	0.80	0.97	1.12	1.30	1.90
RCK_002	0.45	0.60	0.71	0.82	1.00	1.15	1.33	1.94	0.49	0.65	0.77	0.89	1.08	1.24	1.44	2.11
RRD_004	0.15	0.19	0.23	0.27	0.32	0.37	0.44	0.66	0.16	0.21	0.25	0.29	0.35	0.41	0.48	0.72
SCL_001	1.60	2.01	2.30	2.59	3.00	3.35	3.88	5.63	1.76	2.21	2.52	2.84	3.30	3.68	4.26	6.19
SCL_002	1.88	2.36	2.68	3.02	3.51	3.91	4.52	6.56	2.06	2.59	2.95	3.32	3.85	4.29	4.96	7.20
SCL_003	2.30	2.88	3.27	3.67	4.25	4.72	5.46	7.92	2.52	3.16	3.59	4.03	4.65	5.17	5.98	8.68
SCLN_011	1.38	1.81	2.13	2.47	2.98	3.42	4.02	6.03	1.51	1.98	2.32	2.69	3.24	3.73	4.38	6.57
SCLS_001	0.43	0.54	0.63	0.71	0.84	0.95	1.09	1.57	0.47	0.59	0.69	0.78	0.92	1.03	1.19	1.71
SCLS_002	3.67	4.65	5.34	6.07	7.13	8.03	9.36	13.78	4.03	5.11	5.87	6.67	7.83	8.82	10.29	15.14
SCLS_003	0.92	1.16	1.32	1.49	1.74	1.95	2.25	3.26	1.01	1.28	1.46	1.65	1.92	2.14	2.48	3.59
SCLS_004	1.04	1.32	1.51	1.70	1.98	2.21	2.56	3.70	1.15	1.45	1.66	1.87	2.18	2.44	2.82	4.08
TNR_001	0.04	0.05	0.06	0.07	0.08	0.10	0.12	0.17	0.04	0.06	0.07	0.08	0.09	0.11	0.13	0.19
TNR_002	0.58	0.77	0.90	1.05	1.27	1.47	1.77	2.77	0.64	0.84	0.99	1.15	1.40	1.61	1.94	3.04

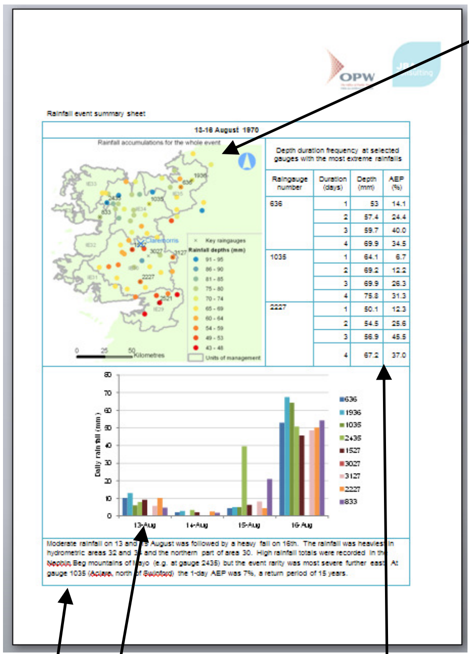
HEP label	Future peak flow - MRFS (m^3/s) by AEP(%)								Future peak flow - HEFS (m^3/s) by AEP(%)							
	50	20	10	5	2	1	0.5	0.1	50	20	10	5	2	1	0.5	0.1
TNR_003	0.67	0.88	1.04	1.21	1.47	1.69	2.01	3.09	0.73	0.97	1.14	1.33	1.61	1.86	2.21	3.38
TNR_004	0.80	1.06	1.25	1.46	1.77	2.04	2.42	3.70	0.88	1.17	1.38	1.60	1.94	2.23	2.65	4.06
TUL_012	1.91	2.41	2.77	3.15	3.70	4.17	4.85	7.15	2.07	2.62	3.00	3.41	4.01	4.52	5.26	7.76

G Analysis of rainfall data

Introduction to Rainfall event summary sheets

This appendix provides results from analysis of rainfall events. Most of the analysis has been carried out using daily rainfall data as there are very few sub-daily gauges in the study area. However, some more simplified sheets show analysis of sub-daily data to aid in understanding the characteristics of short-duration rainfall events.

Information provided in the summary sheets



Map of rainfall depths

The map shows the total accumulated rainfall for the range of dates given in the heading of the sheet. Gauges included on the map are those that are within or near to catchments in the initial list of Areas for Further Assessment (AFAs) provided at the start of the project. A small number of extra AFAs in other catchments were identified during the flood risk review, but this was completed after the rainfall analysis had been carried out.

The map identifies ten key gauges, spread throughout the study area, for which long records are available.

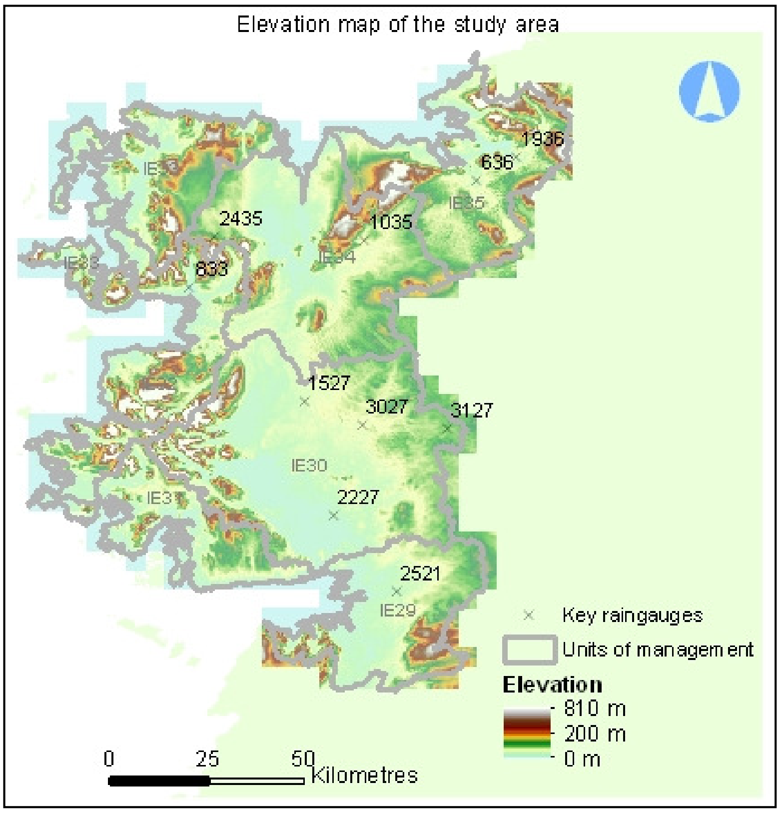
In interpreting the map it is important to bear in mind the general tendency for higher rainfall in the upland areas. The map below shows the topography of the area in relation to the key raingauge locations.

Time series

Series of daily rainfalls at each of the key gauges for which data is available

Commentary

Comments on the characteristics of the event, including any synoptic information available from Met Éireann reports.



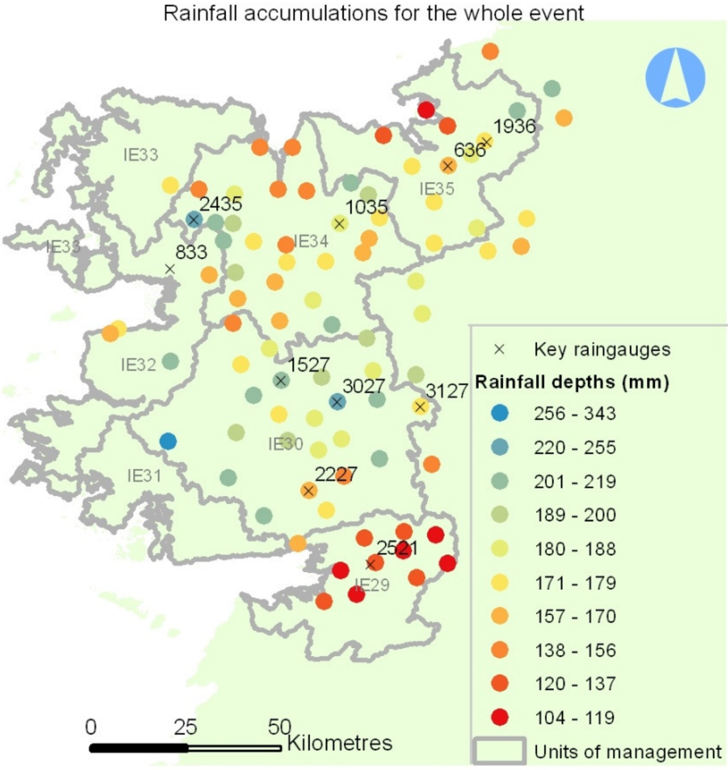
Depth duration frequency analysis

Table of rainfall depths and corresponding annual exceedance probabilities (AEPs) for the maximum rainfall accumulated over a range of durations at selected raingauges. The gauges included in this analysis are those where the rainfall was most notable, i.e. the AEPs were the lowest. The durations have been chosen to be appropriate to the nature of the event, with up to 14 days used for prolonged periods of rainfall. AEPs are calculated from the FSU rainfall frequency statistics.

Rainfall event summary sheet

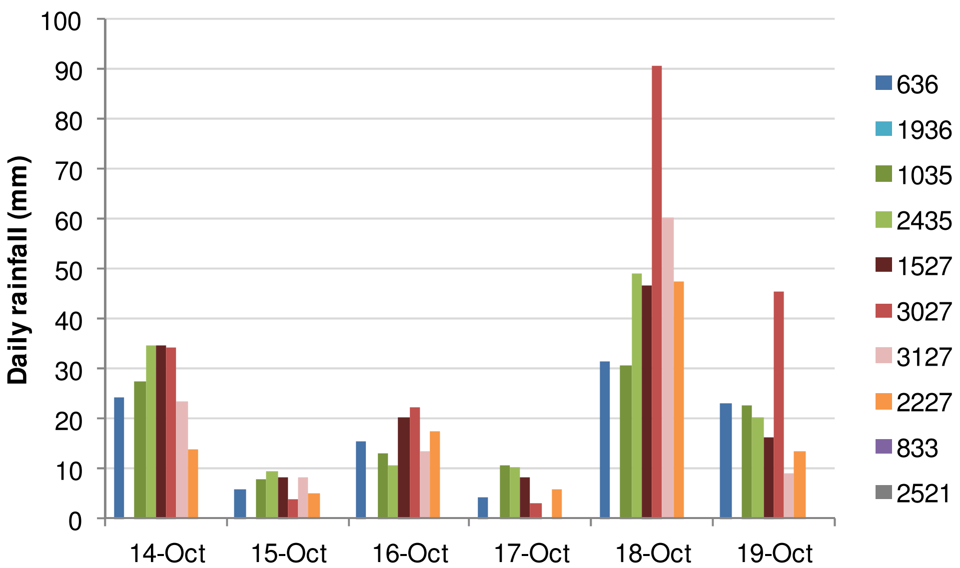
14 to 19 October 1954

Rainfall accumulations for the whole event



Depth duration frequency at selected gauges with the most extreme rainfalls

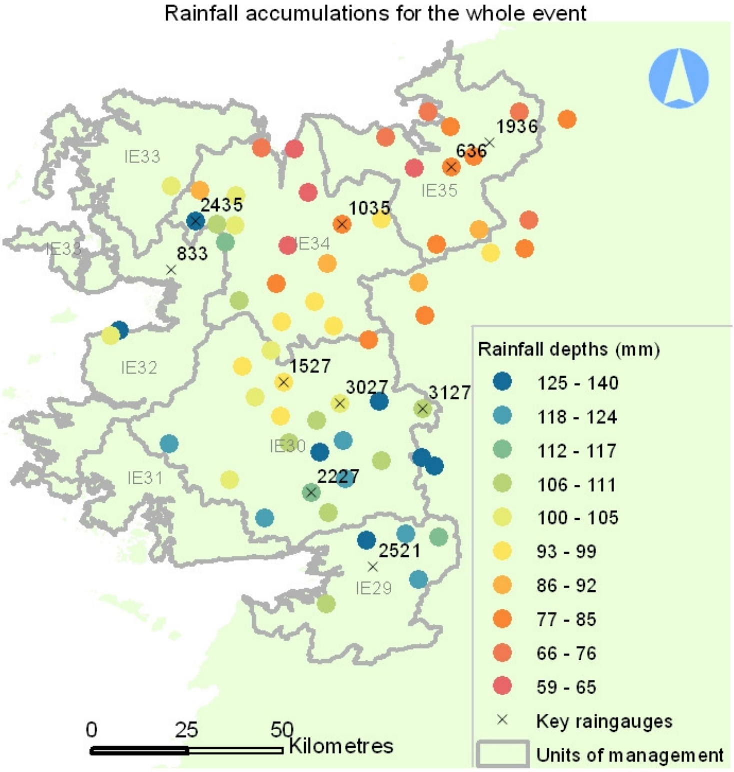
Raingauge number	Duration (days)	Depth (mm)	AEP (%)
1527	1	46.8	31.3
	2	63.3	20.0
	4	92.3	10.0
	6	135.6	1.8
3027	1	90.8	1.4
	2	136.3	0.3
	4	161.9	0.2
	6	200	0.13
3127	1	60.3	7.1
	2	69.6	8.3
	4	83.1	12.0
	6	115	4.3



Several days of rainfall culminated in large daily totals on 18 October 1954. The rain affected the whole of the Western RBD although it was most severe in hydrometric area 30, with an AEP below 1% at gauge 3027, Milltown (between Tuam and Claremorris), for durations over 1 day. For a duration of 6 days, the AEP at Milltown was as low as 0.13% (a return period of 800 years).

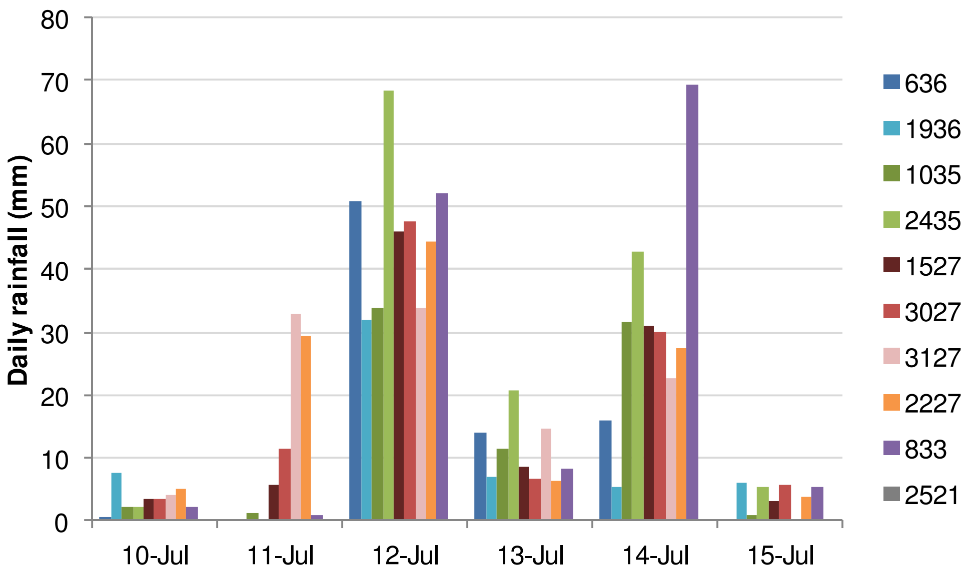
Rainfall event summary sheet

10 to 15 July 1961



Depth duration frequency at selected gauges with the most extreme rainfalls

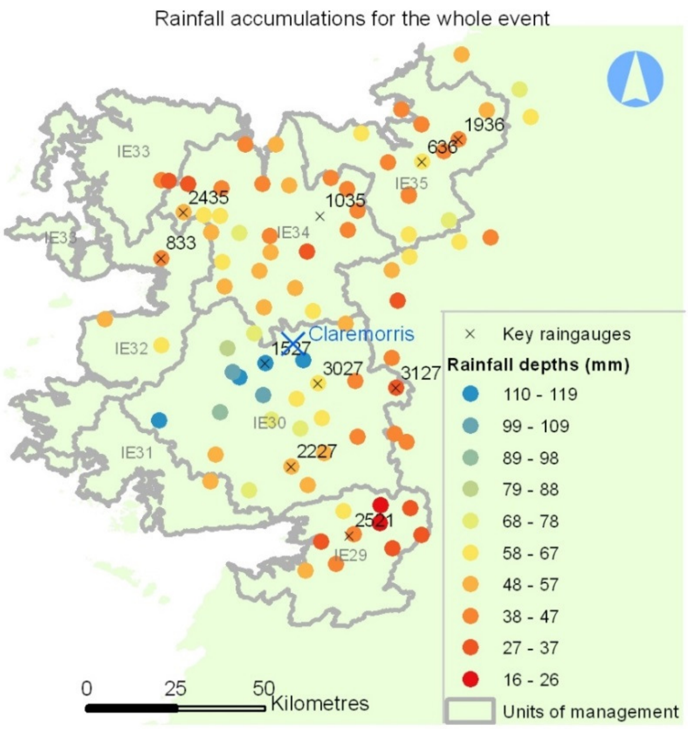
Raingauge number	Duration (days)	Depth (mm)	AEP (%)
3127	1	33.9	59
	2	66.9	10
	3	81.7	7
	4	104.4	3
2227	1	44.3	26
	2	73.7	3
	3	80.1	5
	4	107.5	1
833	1	69.4	15
	2	77.8	24
	3	129.8	3
	4	135.3	5



This summer event affected the whole of the Western RBD, although the largest 6-day accumulations were in hydrometric areas 29 and 30, in the area between Athenry and Claremorris. The majority of the rainfall fell on 12 and 14 July. AEPs were as low as 1% over a duration of 4 days.

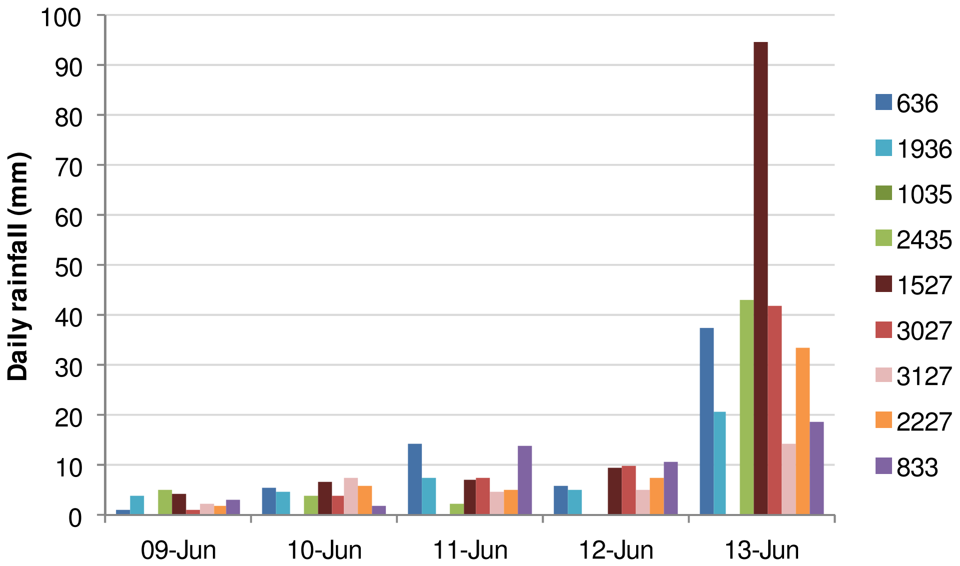
Rainfall event summary sheet

10 to 14 June 1964



Depth duration frequency at selected gauges with the most extreme rainfalls

Raingauge number	Duration (days)	Depth (mm)	AEP (%)
1527	1	94.7	0.9
	2	104.4	1.1
	3	111.5	1.4
	4	118.4	1.7
3027	1	41.8	37.0
	2	51.6	37.0
	4	59.3	37.0
	6	63.1	45.5



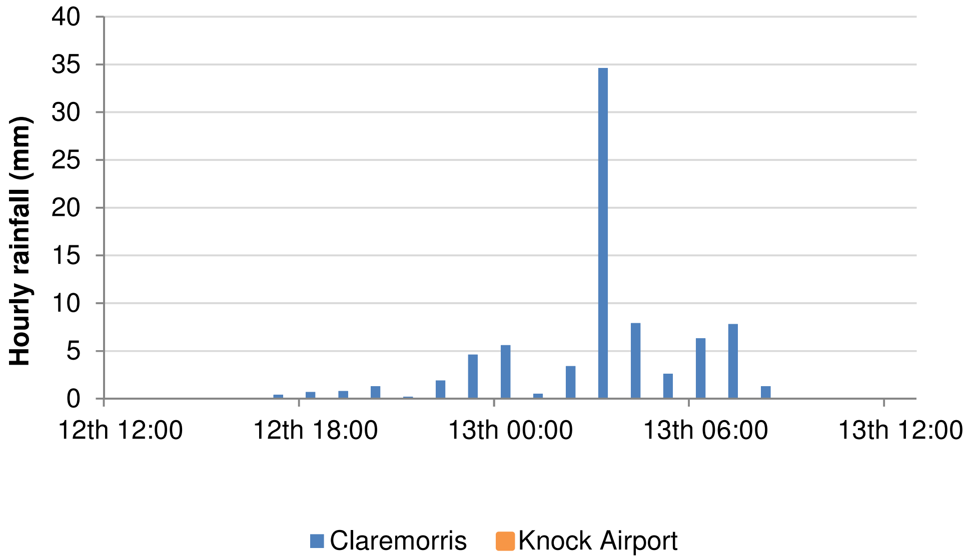
This summer event occurred during a period of light to moderate rain across the whole Western RBD, but the intense rainfall on 13 June was concentrated in the north of hydrometric area 30, between Lough Corrib and Claremorris. At gauge 1527 (Hollymount) the AEP of the 1-day total was 1%. At other key gauges the event was much less extreme. The next page summarises analysis of sub-daily rainfall data.

Analysis of hourly rainfall data

The short, intense nature of this event indicates that analysis of sub-daily rainfall data is worthwhile. Data is available from one gauge in the study area, Claremorris (see the map on the previous page).

Depth duration frequency at Claremorris		
Duration (hours)	Depth (mm)	AEP (%)
1	34.6	1.2
2	42.5	1.2
3	55.1	0.7
4	61.4	0.6
6	72.6	0.5
9	83.3	<0.5
12	86.7	0.6

Note: it is likely that the maximum rainfall accumulated over a sliding duration of 60 minutes during the event was higher than the 1-hour depth given here which refers to the amount of rainfall accumulated within each clock hour. The AEPs here are calculated using the FSU methodology which was based on rainfall data for durations as short as 15 minutes. Thus there may be a bias in the AEPs reported for short durations, particularly 1-2 hours.



During an event which lasted around 10 hours at Claremorris there was an exceptionally heavy burst of rainfall, 34.6mm in 1 hour between 0200 and 0300 on 13 June. Over all accumulation durations from 1 to 24 hours this is the highest rainfall recorded to date at Claremorris (1950-2010).

The AEP of the 1-hour total was 1.2%, i.e. a return period of 80 years. Over the full duration of the event, the AEP was just under 0.5, i.e. a return period over 200 years. This is consistent with the analysis of the daily rainfall data in the vicinity, for example at gauge 1527. It is likely (although hard to be sure without any other recording raingauge data) that the duration of the event was similar at other nearby locations which recorded large daily totals. Rainfall of this intensity is likely to have resulted in local flooding.

Sub-daily rainfall event summary sheet

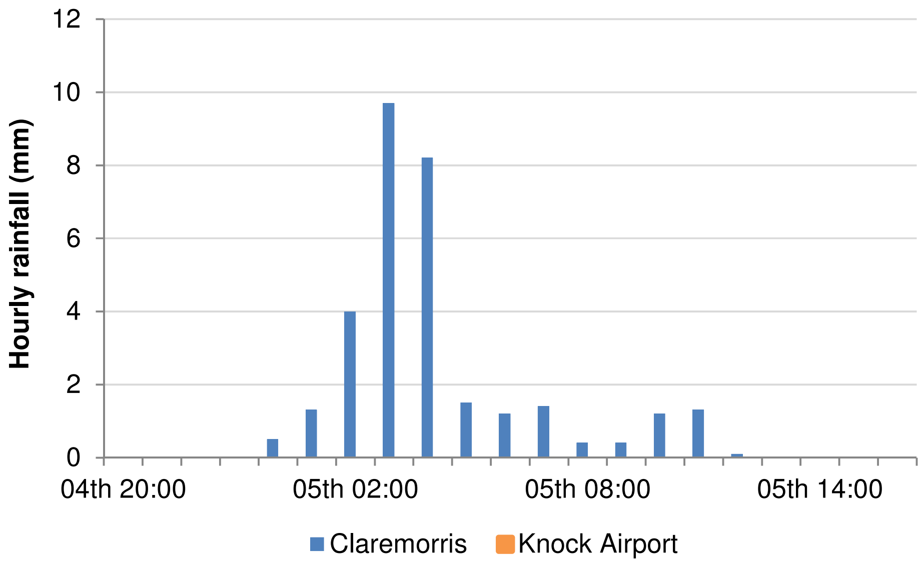
5 October 1964

Hourly rainfall data is available from one gauge in the study area, Claremorris.

Depth duration frequency at Claremorris

Duration (hours)	Depth (mm)	AEP (%)
1	9.7	High
2	17.9	31.1
3	21.9	26.5
4	23.4	29.7
6	24.7	39.0
9	27.3	44.8
12	29.3	49.5

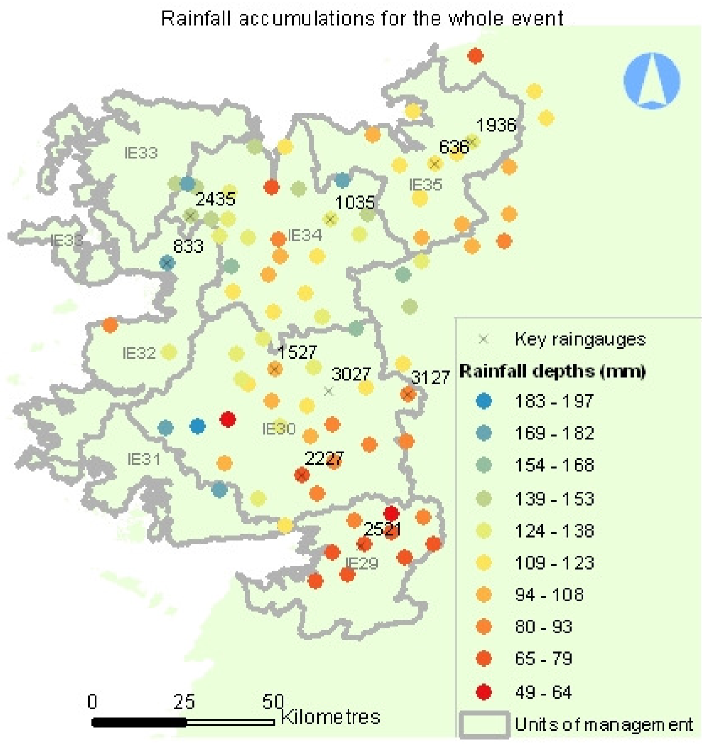
Note: it is likely that the maximum rainfall accumulated over a sliding duration of 60 minutes during the event was higher than the 1-hour depth given here which refers to the amount of rainfall accumulated within each clock hour. The AEPs here are calculated using the FSU methodology which was based on rainfall data for durations as short as 15 minutes. Thus there may be a bias in the AEPs reported for short durations, particularly 1-2 hours.



Heavy rainfall was recorded in the early hours of 5 October. Over a duration of 2-4 hours the AEP was around 30%, i.e. a return period of 3 years.

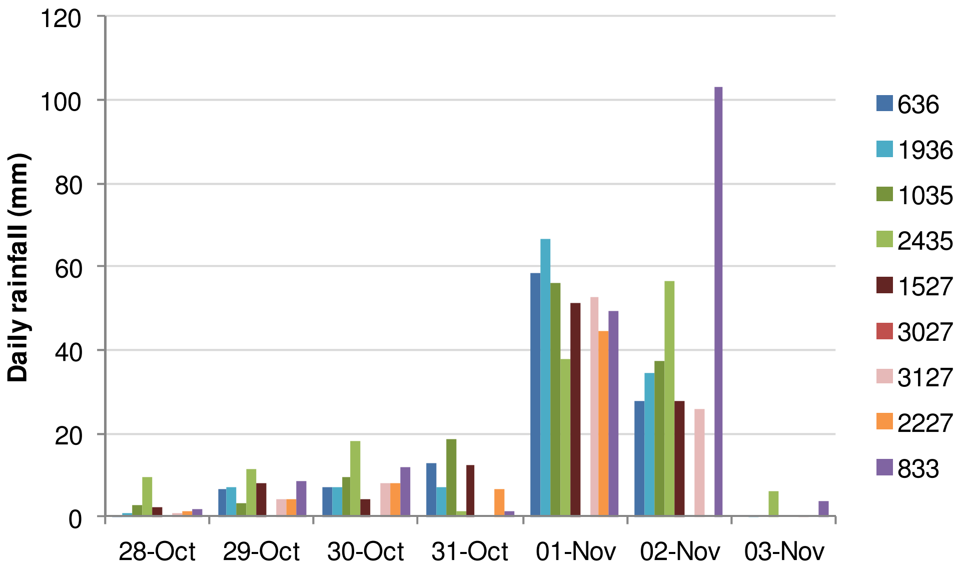
Rainfall event summary sheet

29 October to 2 November 1968



Depth duration frequency at selected gauges with the most extreme rainfalls

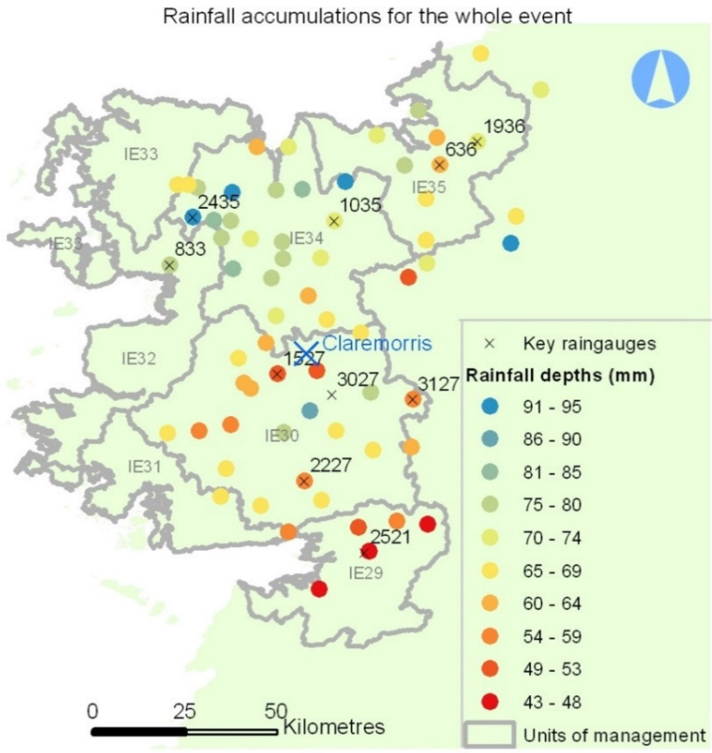
Raingauge number	Duration (days)	Depth (mm)	AEP (%)
636	1	58.4	8.8
	2	86.4	2.6
	4	106.7	2.5
	6	113.8	4.7
833	1	103	2.2
	2	152.5	0.6
	4	165.7	1.4
	6	177.9	2.6
1035	1	56.3	14.1
	2	93.9	1.7
	4	121.9	1.2
	6	128	2.8



Several days of moderate rainfall in late October were followed by two days of heavy rainfall, 1 and 2 November, affecting all parts of the Western RBD although with much larger totals to the west and north. Rainfall rarities were most notable over a duration of 2-4 days, with AEPs as low as 0.6% (a return period of 160 years) at Newport, north of Westport.

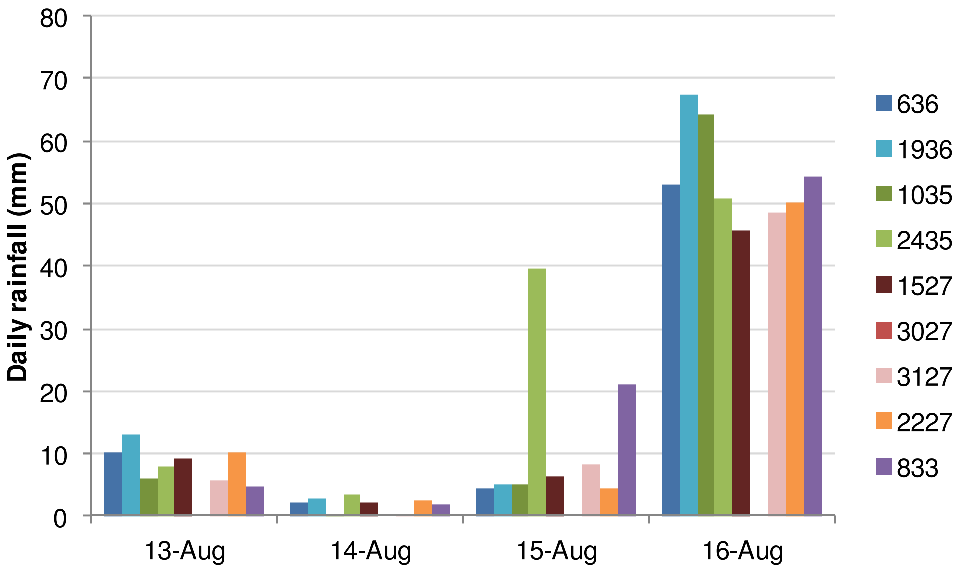
Rainfall event summary sheet

13 to 16 August 1970



Depth duration frequency at selected gauges with the most extreme rainfalls

Raingauge number	Duration (days)	Depth (mm)	AEP (%)
636	1	53	14.1
	2	57.4	24.4
	3	59.7	40.0
	4	69.9	34.5
1035	1	64.1	6.7
	2	69.2	12.2
	3	69.9	26.3
	4	75.8	31.3
2227	1	50.1	12.3
	2	54.5	25.6
	3	56.9	45.5
	4	67.2	37.0



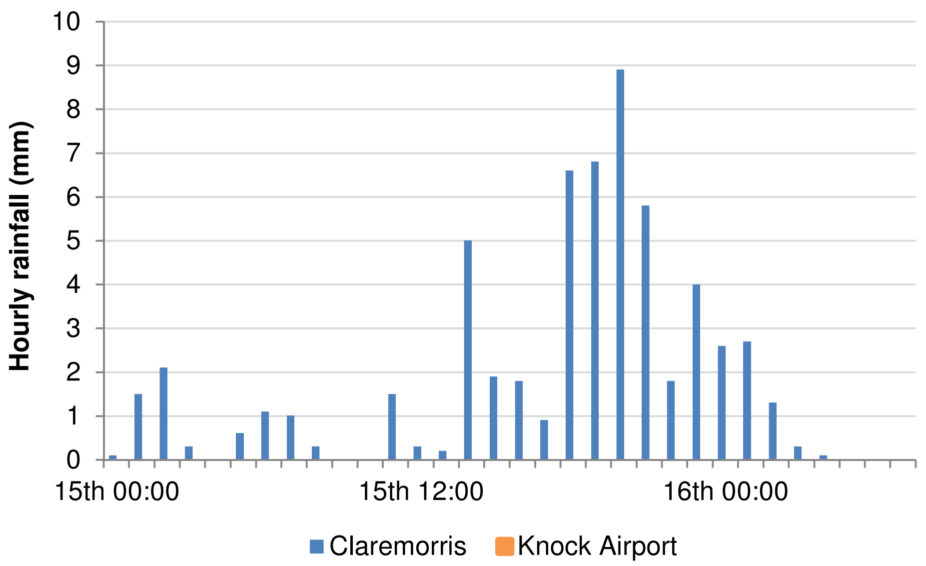
Moderate rainfall on 13 and 15 August was followed by a heavy fall on 16th. The rainfall was heaviest in hydrometric areas 32 and 34 and the northern part of area 30. High rainfall totals were recorded in the Nephin Beg mountains of Mayo (e.g. at gauge 2435) but the event rarity was most severe further east. At gauge 1035 (Aclare, north of Swinford) the 1-day AEP was 7%, a return period of 15 years.

Analysis of hourly rainfall data

The short, intense nature of this event indicates that analysis of sub-daily rainfall data is worthwhile. Data is available from one gauge in the study area, Claremorris (shown on the map on the last page).

Depth duration frequency at Claremorris		
Duration (hours)	Depth (mm)	AEP (%)
1	15.7	22.0
2	22.3	15.5
3	28.1	11.2
4	29.9	12.8
6	36.5	10.1
9	43.5	8.7
12	50.1	7.2

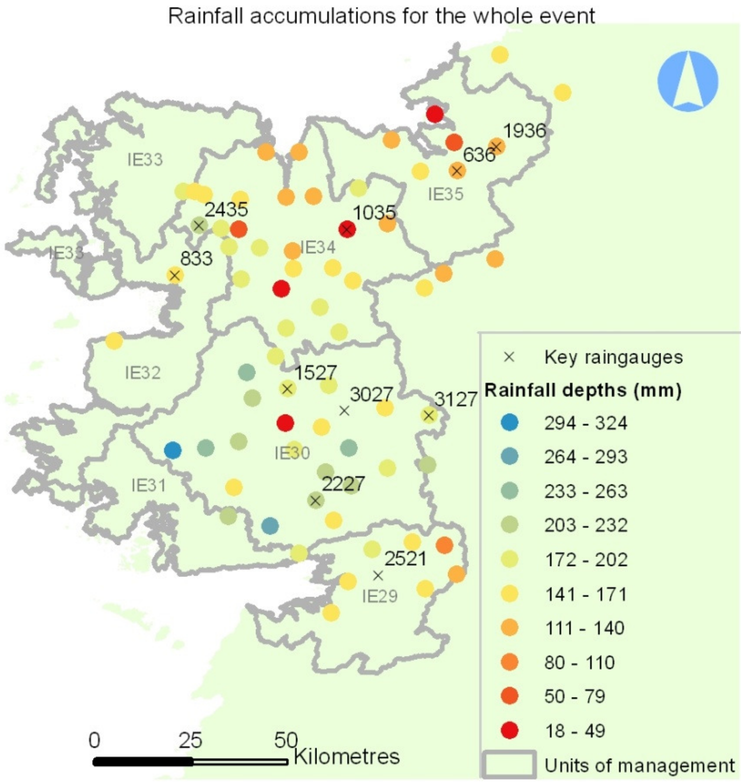
Note: it is likely that the maximum rainfall accumulated over a sliding duration of 60 minutes during the event was higher than the 1-hour depth given here which refers to the amount of rainfall accumulated within each clock hour. The AEPs here are calculated using the FSU methodology which was based on rainfall data for durations as short as 15 minutes. Thus there may be a bias in the AEPs reported for short durations, particularly 1-2 hours.



After light rain on the morning of 15 August, heavy rain fell during the afternoon and overnight into 16 August. The AEPs indicate that the rainfall was not particularly extreme at Claremorris. It can be seen from the map that the rainfall was heavier further north and also to the south.

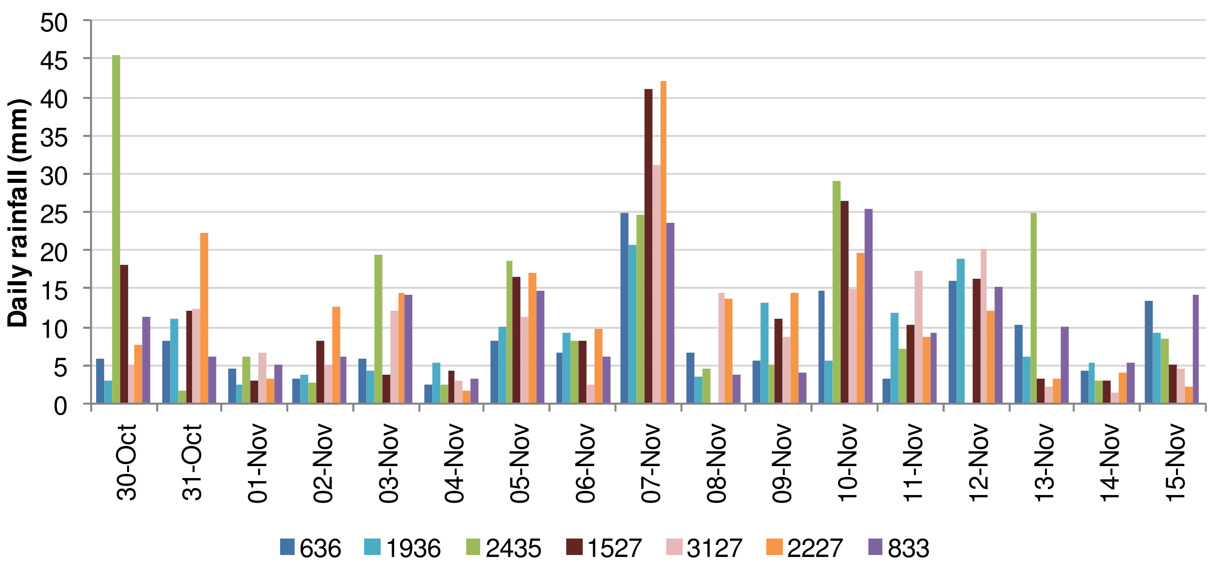
Rainfall event summary sheet

29 October to 14 November 1977



Depth duration frequency at selected gauges with the most extreme rainfalls

Raingauge number	Duration (days)	Depth (mm)	AEP (%)
1527	1	46.9	31.3
	4	78.7	24.4
	7	113.7	11.2
	14	179.5	4.3
3127	1	31.2	71.4
	4	69.5	32.3
	7	109.3	9.8
	14	165.1	5.6
2227	1	42.1	33.3
	4	89.8	4.7
	7	125.4	2.2
	14	199.6	0.7



Prolonged rainfall frequently occurs in late Autumn. In 1977 there was some rain every day from late September to late November. The highest falls were in early November, particularly over hydrometric area 30 and the south of 34. The map shows a few raingauges in this area with much lower rain but this is probably due to missing data. Further north, around Sligo, there was much less rain. The maximum accumulation over a 2-week period was not particularly extreme at most gauges, but at 2227 (Carndolla, between Galway and Headford) the AEP was as low as 0.7% (a return period of 150 years).

Sub-daily rainfall event summary sheet

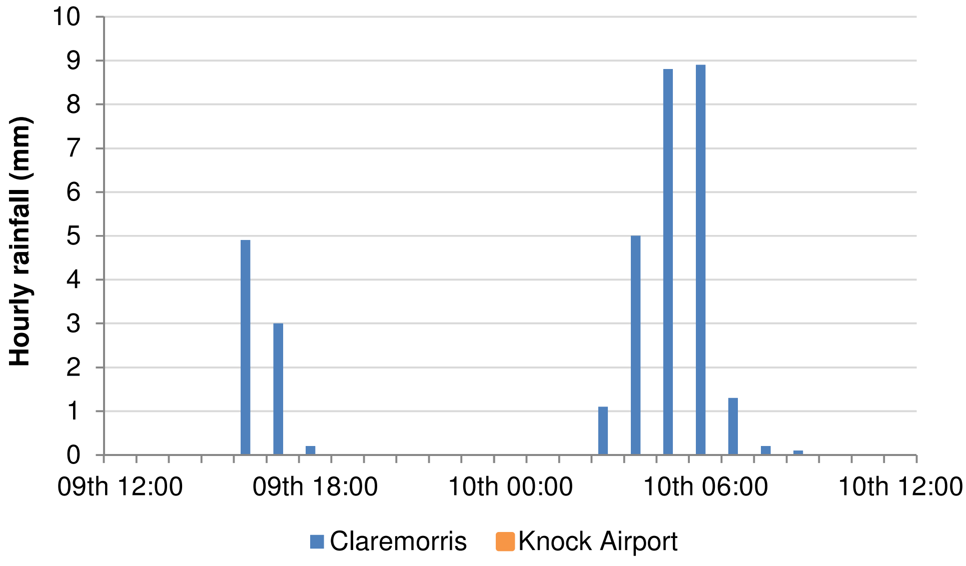
10 September 1981

Hourly rainfall data is available from one gauge in the study area, Claremorris.

Depth duration frequency at Claremorris

Duration (hours)	Depth (mm)	AEP (%)
1	8.9	High
2	17.7	32.1
3	22.7	23.7
4	24	27.5
6	25.1	37.3
9	25.4	High
12	25.4	High

Note: it is likely that the maximum rainfall accumulated over a sliding duration of 60 minutes during the event was higher than the 1-hour depth given here which refers to the amount of rainfall accumulated within each clock hour. The AEPs here are calculated using the FSU methodology which was based on rainfall data for durations as short as 15 minutes. Thus there may be a bias in the AEPs reported for short durations, particularly 1-2 hours.



After a brief shower on the afternoon of 9 September, heavy rainfall was recorded early in the morning on 10 September. The lowest AEP was for the 3-hour accumulation of 22.7mm, which has an AEP of 24%, i.e. return period of 4 years.

Sub-daily rainfall event summary sheet

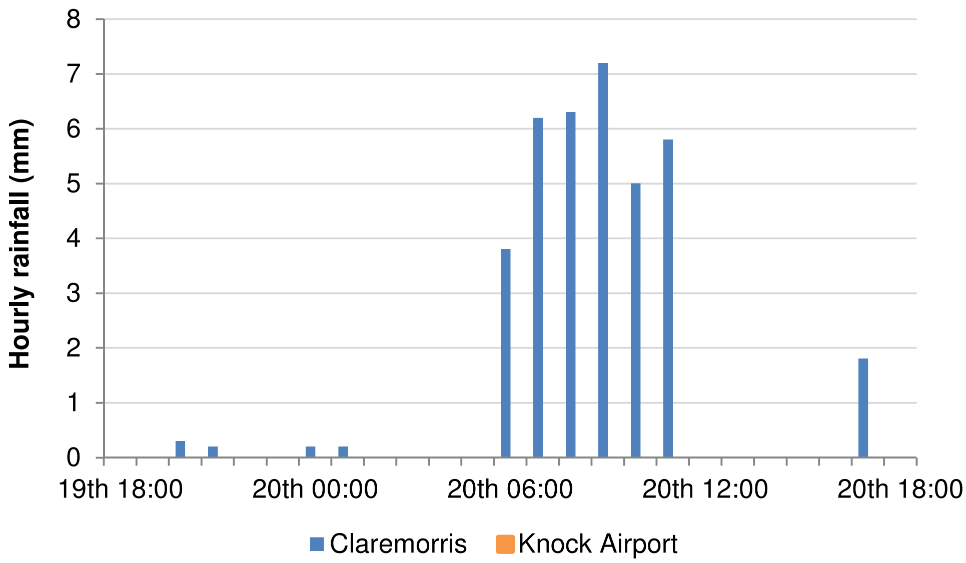
20 August 1987

Hourly rainfall data is available from one gauge in the study area, Claremorris.

Depth duration frequency at Claremorris

Duration (hours)	Depth (mm)	AEP (%)
1	7.2	High
2	13.5	High
3	19.7	36.2
4	24.7	25.1
6	34.3	13.0
9	34.3	22.1
12	36.1	26.4

Note: it is likely that the maximum rainfall accumulated over a sliding duration of 60 minutes during the event was higher than the 1-hour depth given here which refers to the amount of rainfall accumulated within each clock hour. The AEPs here are calculated using the FSU methodology which was based on rainfall data for durations as short as 15 minutes. Thus there may be a bias in the AEPs reported for short durations, particularly 1-2 hours.

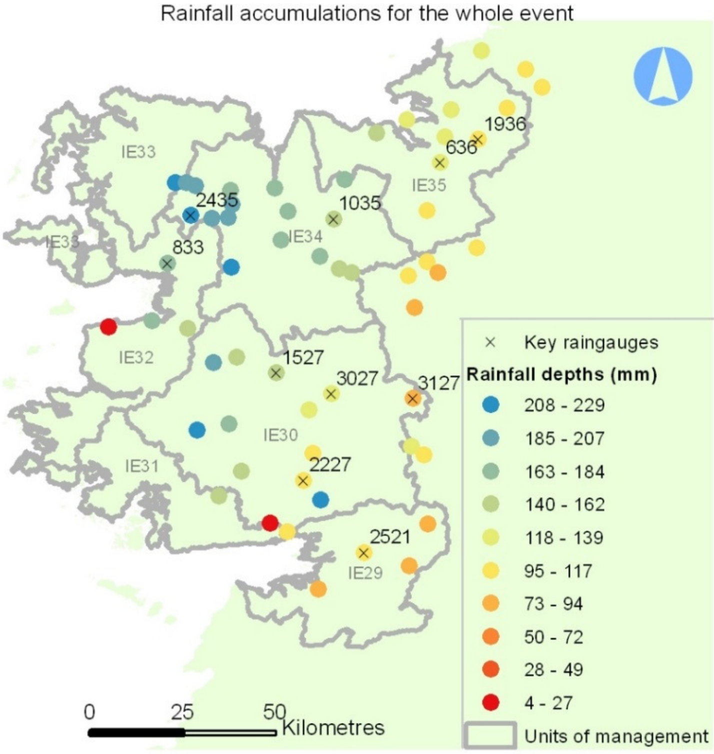


Warm and humid weather, associated with southerly winds, brought periods of heavy rainfall during mid-August. This short rainfall event lasted for 6 hours on the morning of 20 August. The 6-hour accumulation at Claremorris had an AEP of 13%, i.e. a return period of 8 years.

Rainfall event summary sheet

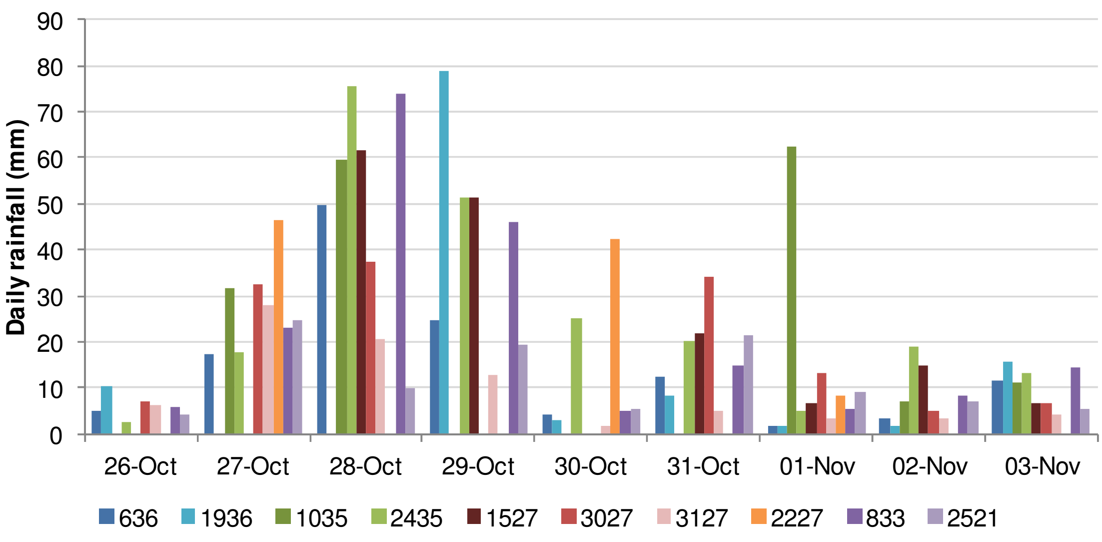
26 October to 2 November 1989

Rainfall accumulations for the whole event



Depth duration frequency at selected gauges with the most extreme rainfalls

Raingauge number	Duration (days)	Depth (mm)	AEP (%)
1035	1	62.5	7.8
	4	96.3	6.8
	6	153.7	0.6
	8	172.1	0.7
1527	1	61.4	9.2
	4	134.4	0.7
	6	155.7	0.6
	8	173.1	0.6
833	1	73.7	11.6
	4	148.6	2.8
	6	168.4	3.8
	8	190.5	4.2

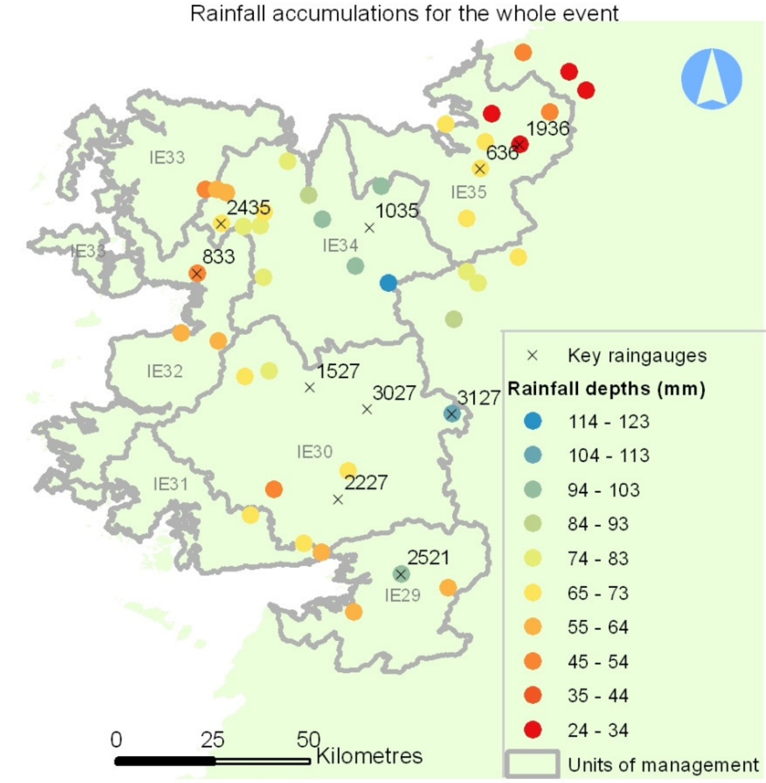


Rainfall affected all of the study area from 5 October to mid-November 1989 and was most severe in late October when a depression approached the extreme SW of Ireland and then moved east, resulting in a slow-moving band of rain associated with a warm front. The largest falls were over the Galway and Mayo mountains and over much of hydrometric areas 30, 32, 33 and 34. The two red spots on the map are probably due to periods of missing data. At Belmullet (NW corner of County Mayo) it was the wettest October since records began, with 129mm recorded in a 36- hour period. AEPs were below 1% for accumulations over several days at gauges 1035 (Aclare) and 1527 (Holymount).

Rainfall event summary sheet

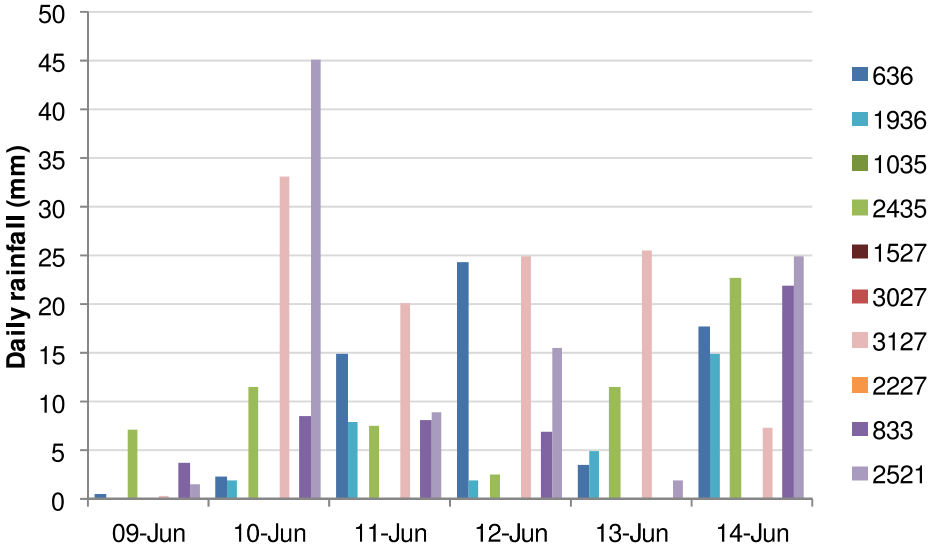
9 to 14 June 1993

Rainfall accumulations for the whole event



Depth duration frequency at selected gauges with the most extreme rainfalls

Raingauge number	Duration (days)	Depth (mm)	AEP (%)
3127	1	33.2	62.5
	2	53.4	30.3
	3	78.3	9.0
	4	103.8	2.9
2521	45.2	25.6	45.2
	54.2	28.6	54.2
	69.7	14.7	69.7
	71.6	25.0	71.6

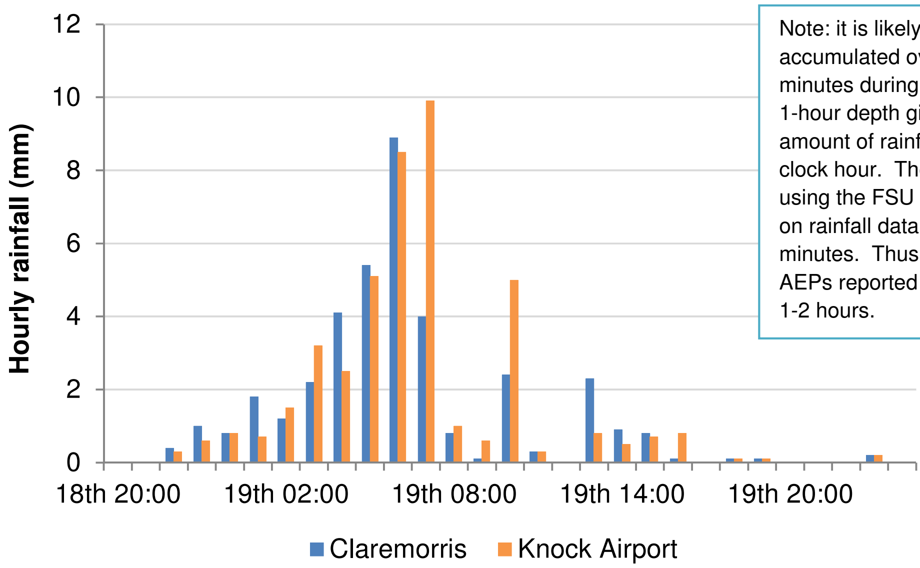


Note that data is missing from several of the key gauges during this event. Rain was caused by a cool northerly airflow due to a depression centred over England and Wales. On 11 June there was very heavy rain in the east midlands and north of Ireland. In the Western RBD, the rainfall over this period was heaviest inland, in the east of hydrometric areas 29, 30 and 34. At gauge 3127 (Glenamaddy, north-east of Tuam) there were four days of notable rainfall, totalling 104mm, with an AEP of 3% over the 4 days (a return period of 30 years).

19 July 1998

Hourly rainfall data is available from two gauges in the study area, Claremorris and Knock Airport.

Depth duration frequency at Claremorris			Depth duration frequency at Knock Airport		
Duration (hours)	Depth (mm)	AEP (%)	Duration (hours)	Depth (mm)	AEP (%)
1	8.9	High	1	9.9	High
2	14.3	High	2	18.4	33.1
3	18.4	43.4	3	23.5	24.9
4	22.4	33.7	4	26	25.1
6	25.8	34.4	6	30.7	23.4
9	29.4	36.2	9	37.3	19.8
12	32.7	36.2	12	39.4	23.2



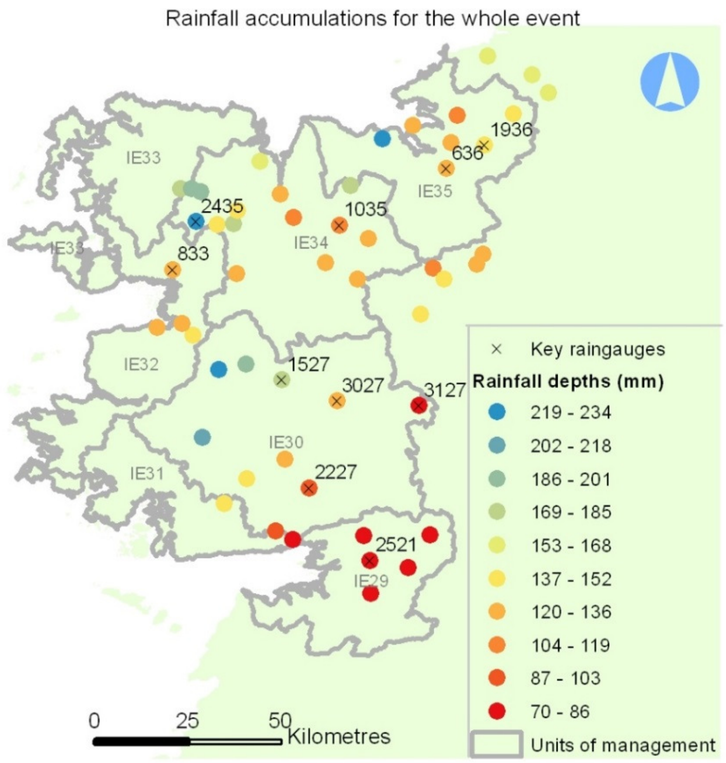
Note: it is likely that the maximum rainfall accumulated over a sliding duration of 60 minutes during the event was higher than the 1-hour depth given here which refers to the amount of rainfall accumulated within each clock hour. The AEPs here are calculated using the FSU methodology which was based on rainfall data for durations as short as 15 minutes. Thus there may be a bias in the AEPs reported for short durations, particularly 1-2 hours.

19 July was a cloudy day with close to normal temperatures. There were spells of rain, some heavy and thunder, across much of Ireland apart from the east coast.

At both raingauges, the event started around midnight on 19 July and continued through the morning. The heaviest rainfall was recorded from 0400 to 0700. The depth of rainfall was similar at the two gauges, and the AEPs indicated that the rainfall was not particularly extreme: typical AEPs were 30-40% at Claremorris and 20-25% (i.e. return periods of 4-5 years) at Knock Airport.

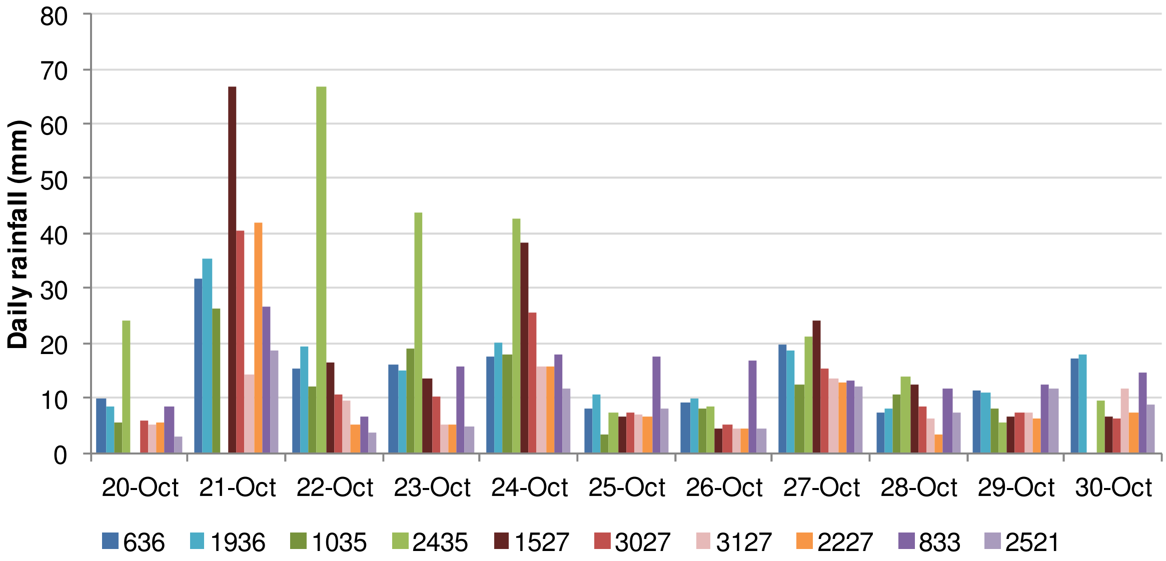
Rainfall event summary sheet

20 to 28 October 1998



Depth duration frequency at selected gauges with the most extreme rainfalls

Raingauge number	Duration (days)	Depth (mm)	AEP (%)
636	1	31.6	71.4
	2	46.8	52.6
	4	80.5	16.1
	7	117.8	5.9
2435	1	66.8	38.5
	2	110.5	8.5
	4	160.7	3.7
	7	204.3	4.0
1527	1	66.6	6.0
	2	82.9	4.3
	4	134.8	0.7
	7	170.2	0.5



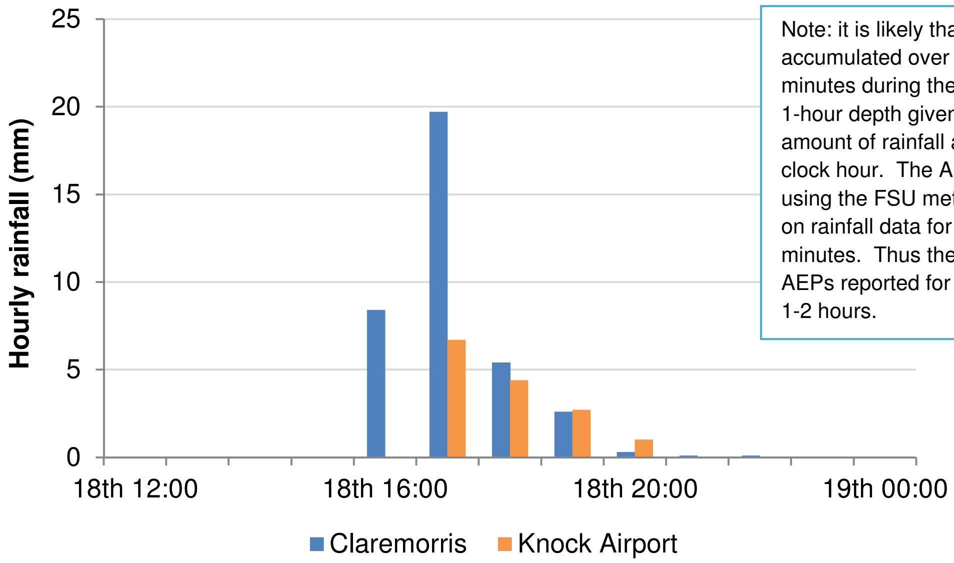
On 20-21 October a deepening depression moved northwards to the west of Ireland bringing heavy frontal rainfall driven by south-easterly gales. There was more widespread and heavier rainfall on 25th. Total October rainfall was near-normal for the western RBD whereas in the SW of Ireland it was the wettest October since 1940. The event impacted all of the Western RBD although totals were lower in hydrometric area 29. It was most extreme at gauge 1527, Hollymount, where the AEP was as low as 0.5% over 1 week of rain – although this may be exaggerated by a possible 2-day accumulation of rain recorded on 21 Oct.

Sub-daily rainfall event summary sheet

18 August 2000

Hourly rainfall data is available from two gauges in the study area, Claremorris and Knock Airport.

Depth duration frequency at Claremorris			Depth duration frequency at Knock Airport		
Duration (hours)	Depth (mm)	AEP (%)	Duration (hours)	Depth (mm)	AEP (%)
1	19.7	10.2	1	6.7	High
2	28.1	6.5	2	11.1	High
3	33.5	5.5	3	13.8	High
4	36.1	6.0	4	14.8	High
6	36.5	10.1	6	14.8	High
9	36.6	17.5	9	14.8	High
12	36.6	25.2	12	14.8	High



Note: it is likely that the maximum rainfall accumulated over a sliding duration of 60 minutes during the event was higher than the 1-hour depth given here which refers to the amount of rainfall accumulated within each clock hour. The AEPs here are calculated using the FSU methodology which was based on rainfall data for durations as short as 15 minutes. Thus there may be a bias in the AEPs reported for short durations, particularly 1-2 hours.

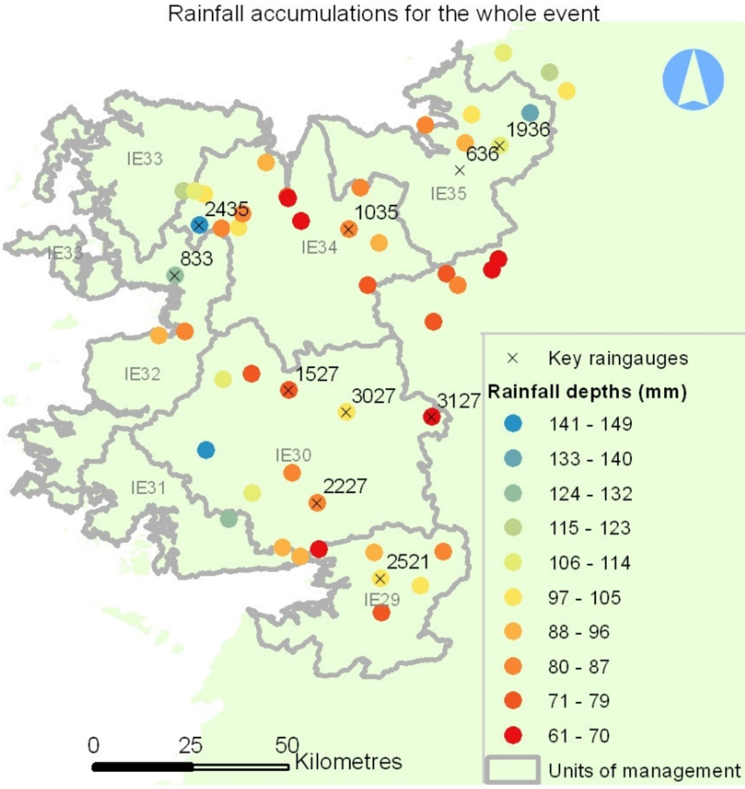
August 2000 was warm and there were frequent thunderstorms between 16th and 21st. On 18th thunder showers were confined to the north-west of Ireland, with temperatures between 16° and 19° C.

This event was a brief burst of rainfall which lasted for a few hours in the late afternoon and early evening of 18 August. At Knock Airport the totals were not noteworthy but at Claremorris the rainfall was intense, resulting in AEPs around 6% for durations 2-4 hours (i.e. return periods around 17 years).

Rainfall event summary sheet

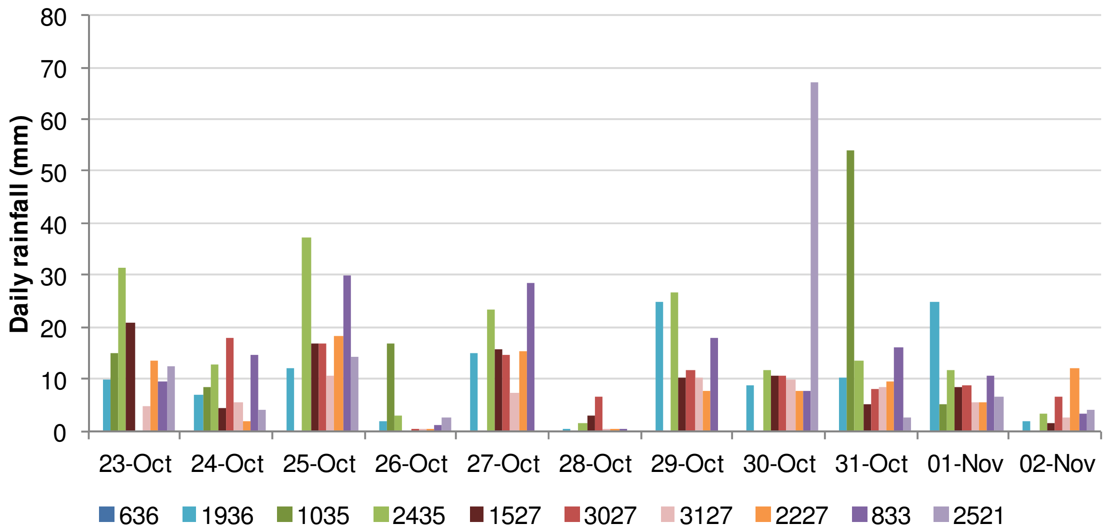
24 October to 2 November 2000

Rainfall accumulations for the whole event



Depth duration frequency at selected gauges with the most extreme rainfalls

Raingauge number	Duration (days)	Depth (mm)	AEP (%)
2521	2	n/a	n/a
	4	80.8	12
	7	92.5	24
	14	142.3	15
2435	2	58.2	>50
	4	87.4	>50
	7	135.8	>50
	14	239.2	28

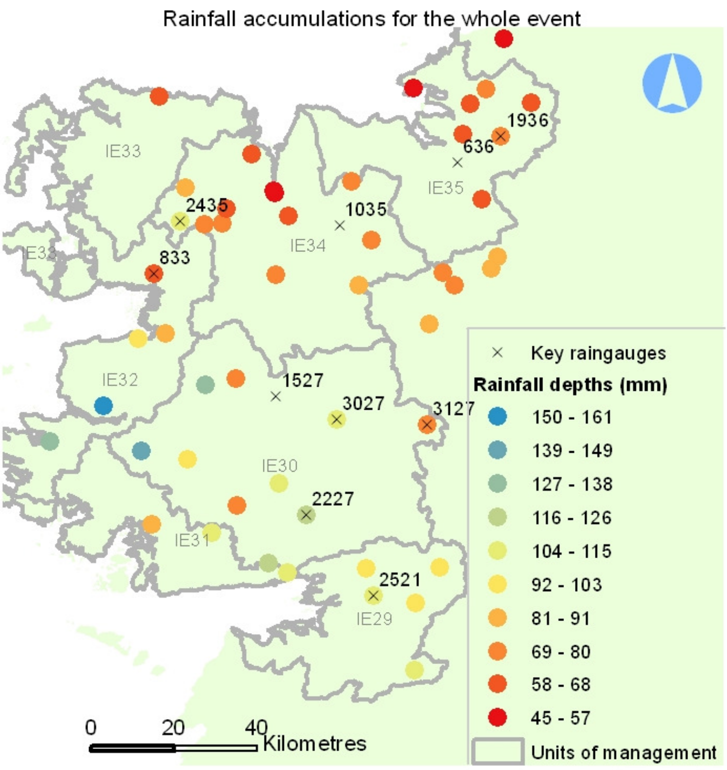


This event affected all of the Western RBD. A succession of Atlantic depressions brought rain almost every day from late August to mid December 2000. The highest totals were observed in late Oct and early Nov, although the event was not particularly severe at any of the key gauges analysed. The lowest AEP was at gauge 2521, Craughwell. In England and Wales the event was much more severe. Over the whole of October, rainfall was highest of any October on record at Galway Airport and Maam Valley.

Note: the reported depth of 67.3mm at gauge 2521 on 30 October was probably in fact an accumulation over four days, as zero rainfall was reported at this gauge for the preceding three days.

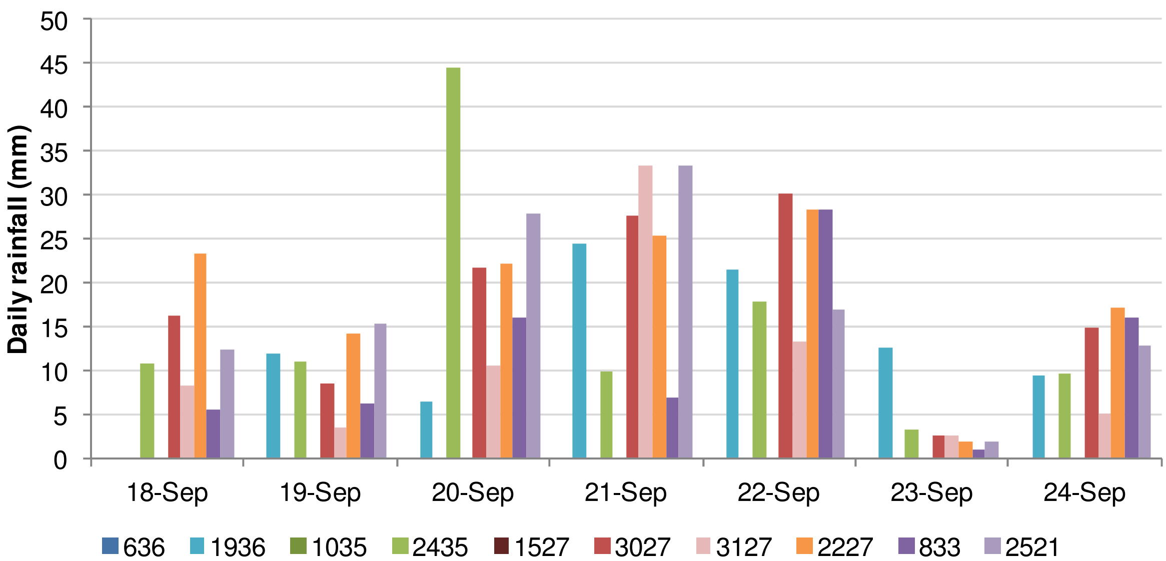
Rainfall event summary sheet

17 to 23 September 2006



Depth duration frequency at selected gauges with the most extreme rainfalls

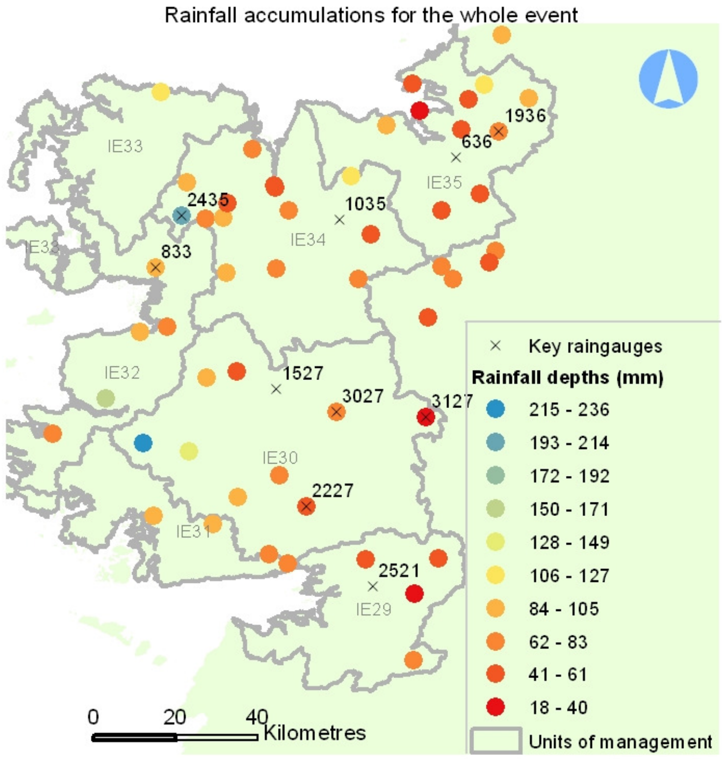
Raingauge number	Duration (days)	Depth (mm)	AEP (%)
3027	1	30.2	76.9
	2	57.9	23.3
	4	88.1	9.6
	7	121.7	5.2
2227	1	28.4	90.9
	2	53.8	27.8
	4	90.1	4.6
	7	132.4	1.3
2521	1	33.4	76.9
	2	61.3	13.7
	4	93.6	4.0
	7	120.7	3.5



This was the warmest September on record in many parts of Ireland. Deep Atlantic depressions brought wet and windy weather. The rain on 20th-21st was caused by the remnants of Hurricane Gordon. This event was more severe in the south of the RBD, with multi-day accumulations having AEPs around 5% in hydrometric areas 29 and 30. The lowest AEP was at gauge 2227, Carndolla, between Galway and Headford, where the maximum 7-day accumulation had an AEP of 1.3% (a return period of 70 years).

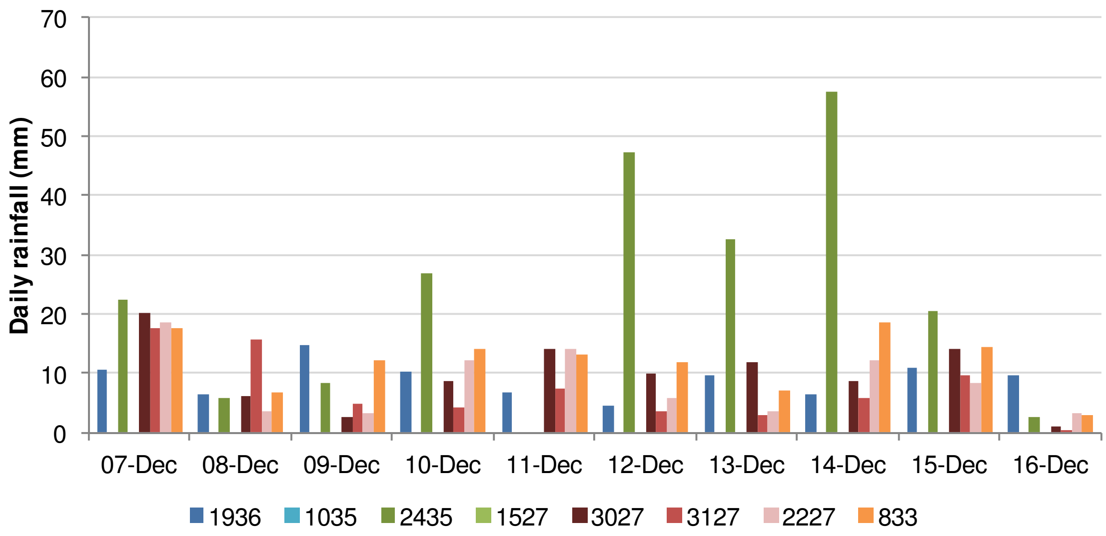
Rainfall event summary sheet

9 to 15 December 2006



Depth duration frequency at selected gauges with the most extreme rainfalls

Raingauge number	Duration (days)	Depth (mm)	AEP (%)
2435	2	101.3	14.7
	4	157.7	4.3
	7	192.8	6.6
	14	368.1	0.4
3027	2	89.4	2.8
	4	118.7	1.7
	7	136.1	2.5
	14	196.6	1.5
2227	2	41.3	76.9
	4	76.4	16.4
	7	118.1	3.7
	14	173	3.0



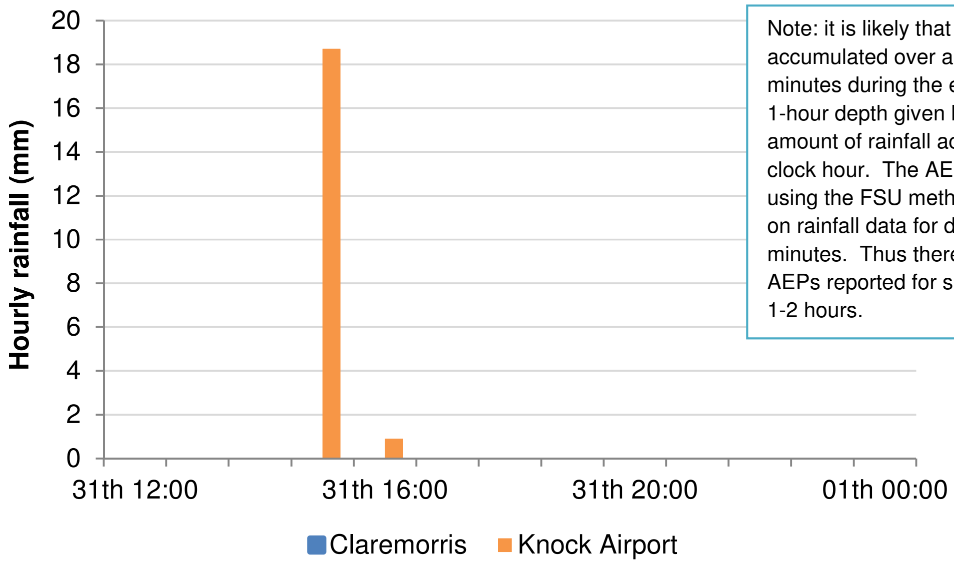
A series of very deep depressions passing to the northwest of Ireland brought rain, accompanied by strong south-westerly winds. There was rain almost every day from 7 November to mid-December. During 9-15 Dec there were exceptionally high totals in the western mountainous areas, particularly at gauge 2435 (Keenagh Beg, in the Nephin Beg hills above Crossmolina) where the AEP over 2 weeks was 0.4%, i.e. a return period of 400 years. The event was also notable in hydrometric area 30, with AEPs of 1-3% at gauges 3027 and 2227. It is possible that some of the low rainfall totals shown on the map are due to missing data.

Sub-daily rainfall event summary sheet

31 May 2008

Hourly rainfall data is available from two gauges in the study area, Claremorris and Knock Airport.

Depth duration frequency at Claremorris			Depth duration frequency at Knock Airport		
Duration (hours)	Depth (mm)	AEP (%)	Duration (hours)	Depth (mm)	AEP (%)
1	0.1	n/a	1	18.7	15.0
2	0.1	n/a	2	19.6	27.7
3	0.1	n/a	3	19.6	41.2
4	0.1	n/a	4	19.6	High
6	0.1	n/a	6	19.6	High
9	0.1	n/a	9	19.6	High
12	0.1	n/a	12	19.6	High



Note: it is likely that the maximum rainfall accumulated over a sliding duration of 60 minutes during the event was higher than the 1-hour depth given here which refers to the amount of rainfall accumulated within each clock hour. The AEPs here are calculated using the FSU methodology which was based on rainfall data for durations as short as 15 minutes. Thus there may be a bias in the AEPs reported for short durations, particularly 1-2 hours.

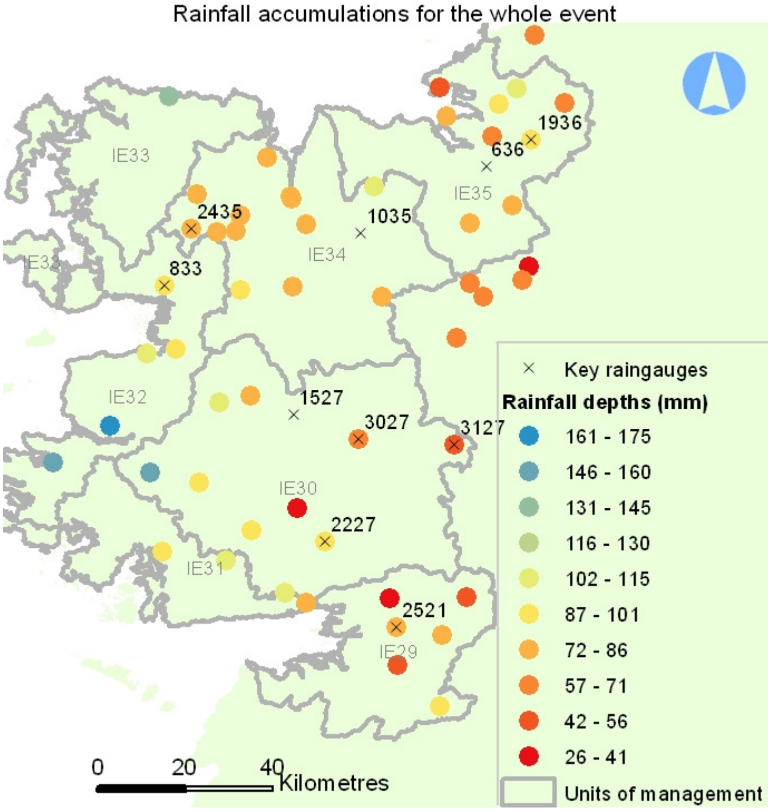
May 2008 was sunny, dry and warm. On May 31st, a thunderstorm in County Mayo resulted in a brief intense fall of rain which was recorded at Knock Airport. 25km to the south-west at Claremorris there was no rain. From the daily rainfall data it appears that the highest rainfall was 25mm at Strade, north-east of Castlebar.

The 1-hour fall of 18.7mm is the highest on record to date at Knock Airport (1996-2010) and had an AEP of 15% (i.e. a return period of 7 years).

Rainfall event summary sheet

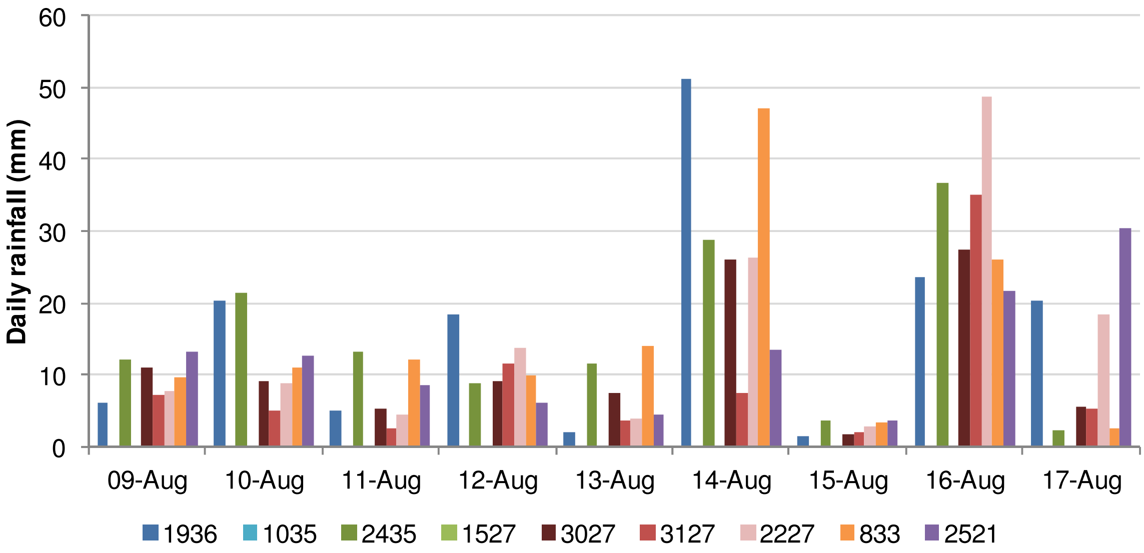
14 to 16 August 2008

Rainfall accumulations for the whole event



Depth duration frequency at selected gauges with the most extreme rainfalls

Raingauge number	Duration (days)	Depth (mm)	AEP (%)
1936	1	51.2	17.2
	2	53.2	43.5
	4	96.4	15.2
	7	121.9	20.4
2227	1	48.6	14.9
	2	66.9	6.5
	4	96	2.7
	7	118.1	3.7
2521	1	30.4	83.3
	2	52.1	34.5
	4	69.2	30.3
	7	88.3	32.3



Low pressure close to or over Ireland brought a succession of Atlantic frontal systems across the country, giving some significant falls on 14th and 16th. It was the wettest August in some parts of Ireland. The event affected all of the Western RBD. It was not particularly severe, with an AEP exceeding 30% at most gauges. The lowest AEP was 3% for the 4-day total at gauge 2227, Carndolla.

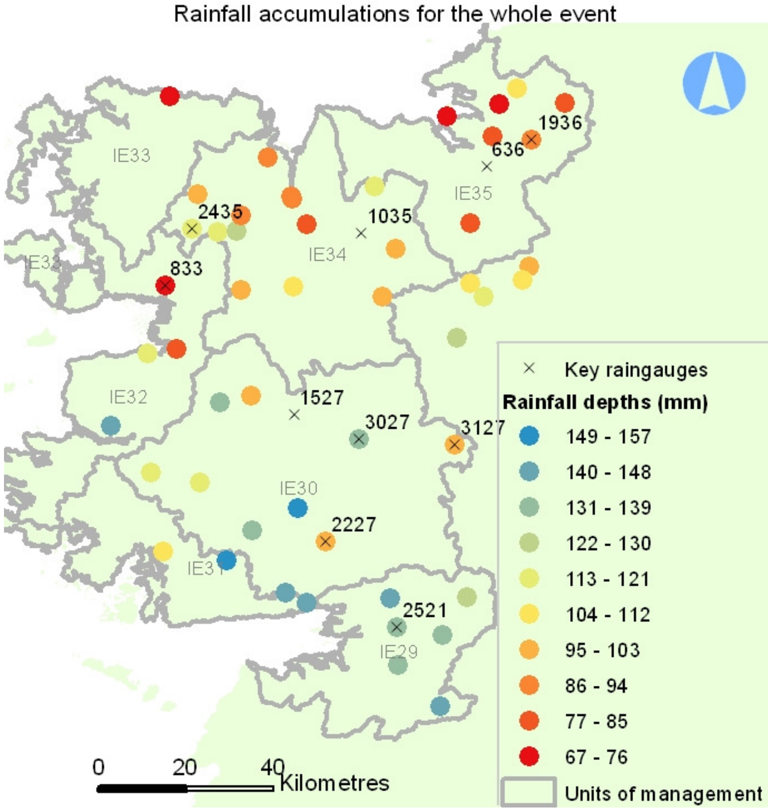
Further information on this event is available in Met Éireann's Climatological Note No. 11.

Note: some of the low rainfalls shown on the map are due to periods of missing data.

Rainfall event summary sheet

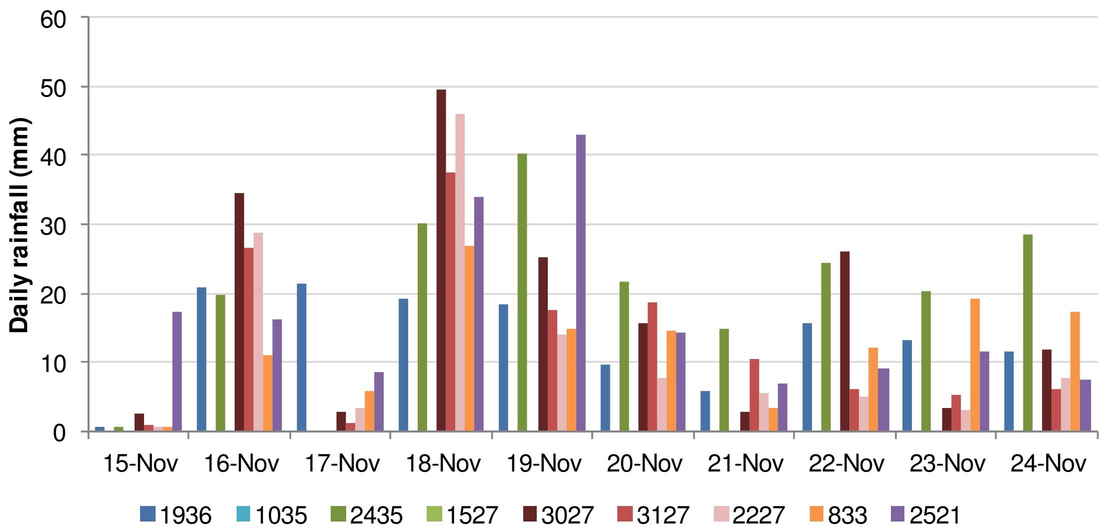
15 to 20 November 2009

Rainfall accumulations for the whole event



Depth duration frequency at selected gauges with the most extreme rainfalls

Raingauge number	Duration (days)	Depth (mm)	AEP (%)
3027	2	74.6	7.1
	4	111.9	2.4
	7	156.2	1.0
	14	210.8	0.9
3127	2	55.1	26.3
	4	84.3	11.1
	7	118.4	5.5
	14	174.4	3.4
2521	2	76.8	2.9
	4	101.4	2.2
	7	146.9	0.7
	14	212.9	0.5



Atlantic depressions passing close to Ireland brought wet and windy conditions throughout almost all of November, continuing a pattern of very unsettled weather over Ireland that began in mid-October. Rainfall totals for November were the highest on record at most stations. In the Western RBD rain fell almost every day from 18 October to 28 November. The highest totals were in the south of the RBD, in hydrometric areas 29 to 31, particularly in the vicinity of Galway. The AEP was below 1% (a return period of 150-200 years) for 1 and 2-week accumulations at gauge 2521, Craughwell, south of Athenry.

Further information on this event is available in Met Éireann's Climatological Note No. 12.

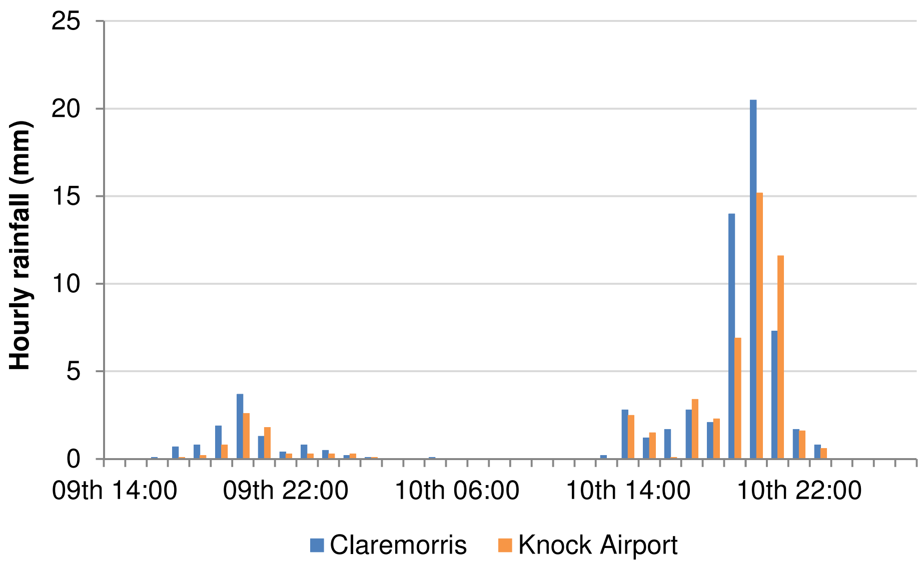
Sub-daily rainfall event summary sheet

10 July 2010

Hourly rainfall data is available from two gauges in the study area, Claremorris and Knock Airport.

Depth duration frequency at Claremorris			Depth duration frequency at Knock Airport		
Duration (hours)	Depth (mm)	AEP (%)	Duration (hours)	Depth (mm)	AEP (%)
1	20.5	8.9	1	15.2	28.1
2	34.5	2.9	2	26.8	9.7
3	41.8	2.2	3	33.7	6.9
4	43.9	2.6	4	36	7.8
6	48.4	3.1	6	41	8.0
9	54.1	3.3	9	45.1	9.5
12	55.1	4.7	12	45.7	13.4

Note: it is likely that the maximum rainfall accumulated over a sliding duration of 60 minutes during the event was higher than the 1-hour depth given here which refers to the amount of rainfall accumulated within each clock hour. The AEPs here are calculated using the FSU methodology which was based on rainfall data for durations as short as 15 minutes. Thus there may be a bias in the AEPs reported for short durations, particularly 1-2 hours.



Rain fell across Ireland most days of July 2010, associated with frontal systems moving eastwards over Ireland, as unusually deep depressions for July tracked close to the west coast. On 10 July maximum temperatures were 16-20°C and winds became stronger through the day. A band of persistent rain in the south of the country during the morning spread northwards to affect all areas by afternoon. Further heavy thundery pulses moved up from the south during the afternoon and evening, producing extremely heavy falls in the west. The rain cleared from the southwest by evening.

The highest rainfall in the country during this event was recorded at Claremorris. At both Claremorris and Knock Airport rain was particularly heavy from 6-9pm. Over a 3-hour duration the AEP was 2.2% at Claremorris (a return period of 50 years) and 7% at Knock Airport.

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