# CASTLEFINN FLOOD RELIEF SCHEME

## Hydrology Report

IBE1760
Rp019 Castlefinn FRS
Hydrology Report
F02
9th June 2023

rpsgroup.com

## Document status

| Version | Purpose of document | Authored by | Reviewed by | Approved by | Review date |
|---|---|---|---|---|---|
| D01 | Draft | M. Buchanan<br>B. Quigley | B. Quigley | A. Jackson | 22/11/2022 |
| DF01 | Draft | M. Buchanan<br>B. Quigley | B. Quigley | A. Jackson | 22/01/2022 |
| F01 | Final Hydrology Report | M. Buchanan<br>B.Quigley | B. Quigley | A. Jackson | 05/08/2022 |
| F02 | Final Hydrology Report | M. Buchanan<br>B.Quigley<br>A. Best | B. Quigley | A. Jackson | 09/06/2022 |

## Approval for issue

Andrew Jackson  9 June 2023



**Prepared by:**

**RPS**

Brendan Quigley
**Technical Director**

Elmwood House
74 Boucher Road, Belfast
Co. Antrim BT12 6RZ

T +44 2890 667 914
E Brendan.Quigley@rpsgroup.com

**Prepared for:**

**Donegal County Council and Steering Group**

# Contents

## Tables



## Figures

# 1 INTRODUCTION

Castlefinn lies on the northern bank of the River Finn, a large sub-catchment of the Foyle catchment. The hydrological analysis for the Castlefinn Flood Relief Scheme (FRS) will consider the flood risk emanating from the River Finn, tributaries and drainage channels which flow through the study area, which have been identified as potentially causing risk to the town of Castlefinn and the surrounding area. The location of Castlefinn town within the study area (Finn catchment) is shown in Figure 1.1. The watercourses to be modelled are shown in Figure 1.2 which includes the River Finn and tributaries known to contribute to flooding in Castlefinn town i.e., Corcullion Watercourse, Castlefinn Watercourse, Bridge Burn, and the Tieveback Watercourse.

This report details the hydrological analysis undertaken in support of Stage 1 of the project - Scheme Development and Design.

## 1.1 CFRAM Study Hydrological Assessment

The hydrological analysis undertaken as part of the CFRAM Study utilised the latest Flood Update Studies (FSU) methodologies and the best available observed data at the time (up to the end of the hydrological year 2013). The hydrological analysis was validated through a review of the modelled flood extents against the best available observed data and historic (1987) flood mapping produced by Department for Infrastructure (DfI) Rivers for the same area.

Following hydrological and hydraulic analysis in the North Western – Neagh Bann (NWNB) CFRAM Study the main source of flood risk to Castlefinn was determined to be fluvial-driven water levels in the River Finn. A number of smaller watercourses, flow through Castlefinn to join the River Finn on its way to Lifford, where it meets the River Mourne to become the River Foyle. The CFRAM Study noted that the flooding extents generated at Castlefinn are sensitive to the water level at the Mourne / Finn confluence at Lifford.

### 1.1.1 Potential Improvements

Given that the main catchment affecting Castlefinn is gauged (Ballybofey – 01043), the design flows are tied to observed data. For that reason, the hydrological analysis must consider the impact of additional years of data on the assumptions regarding flood frequency inherent in the CFRAM Study analysis. The 2015 floods in particular represent significant flood events that when considered within an 'at site' flood frequency analysis may alter the understanding of flood risk. These events may also inform understanding of the timing of hydrographs and Joint Probability assumptions. Furthermore, other improvements could be made to enhance the robustness of the analysis at the scheme level including:

- consideration of the flood risk from other small watercourses and drains affecting Castlefinn;
- increase in the resolution of the hydrological analysis;
- routing of recent flood flow data through the model and;
- incorporating the results of the new hydrological analysis available for the Lifford FRS including rating reviews on hydrometric gauging stations on the Deele at Sandy Mills, the Finn at Ballybofey and the Mourne at Drumnabuoy House.

## 1.2 Catchment Review

The Finn catchment at Castlefinn is approximately 449km$^2$. The total catchment for the Castlefinn study area at its most downstream extent is approximately 502km$^2$. The most upstream extents of the catchment are located at the source of the River Finn in the Bluestack Mountains to the west of Ballybofey.

The catchment characteristics and watersheds associated with the Hydrological Estimation Points (HEPs) are defined within the Flood Estimation Handbook (FEH) and Flood Studies Update (FSU) for those located in

Northern Ireland and the Republic of Ireland respectively. Catchment boundaries and areas were validated through watershed delineation using the best available digital terrain models (DTM) covering the Foyle catchment. Light Detection and Ranging (LiDAR) was used to validate catchment boundaries where available.

The Finn catchment is rural (less than 1% urbanised) with some attenuating features (reservoirs and lakes) in the upper reaches including Lough Finn and Lough Mourne. The catchment is relatively steep and is fairly impermeable with areas of peat cover on high ground and restricted development of river alluvium in valleys. The catchment experiences high sums of rainfall annually, approximately 1700mm. These physiographic and meteorological characteristics result in relatively high flood flows and a flashy response throughout the catchment.

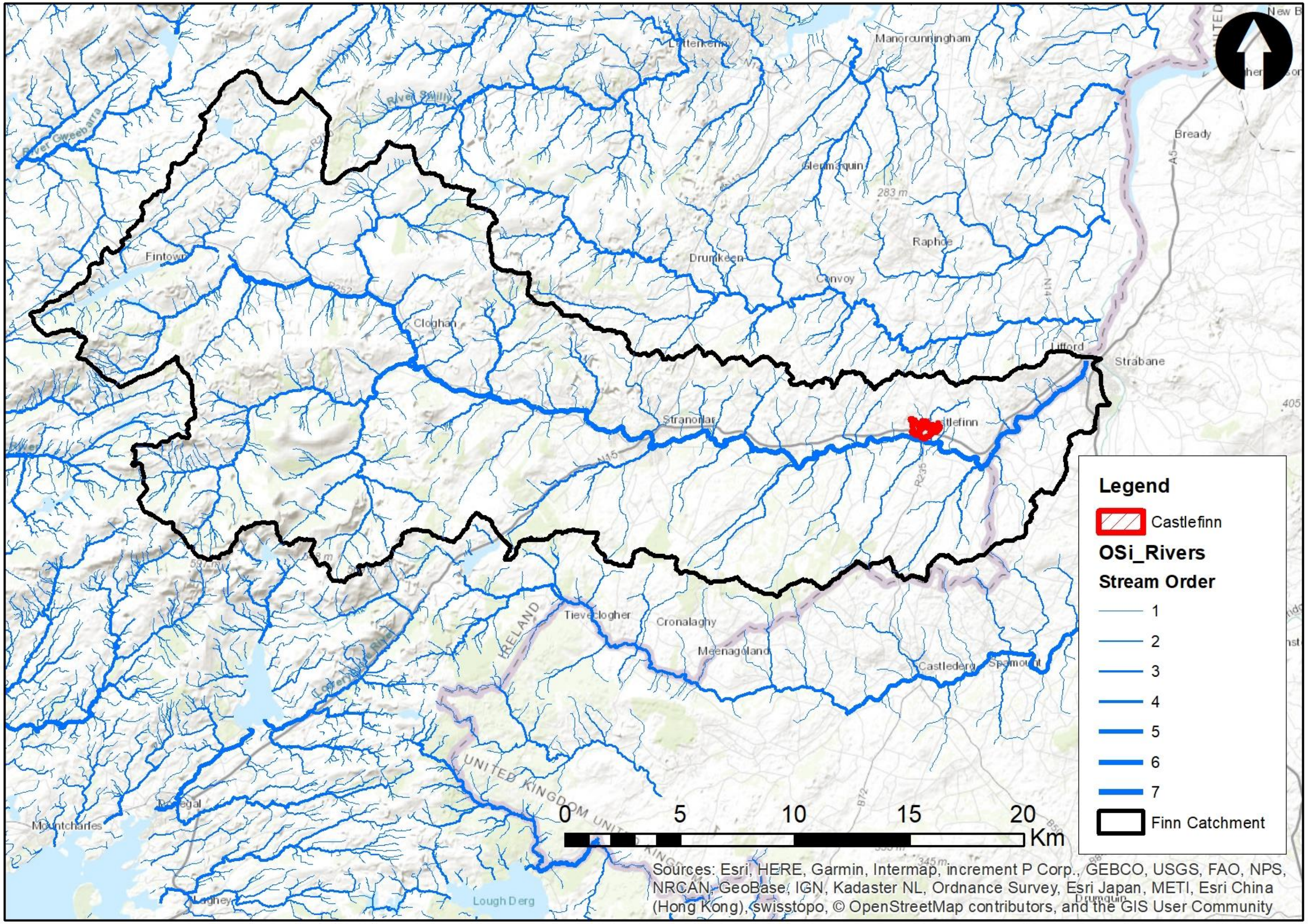


**Figure 1.1 Castlefinn FRS Main Fluvial Catchment (Finn Catchment)**

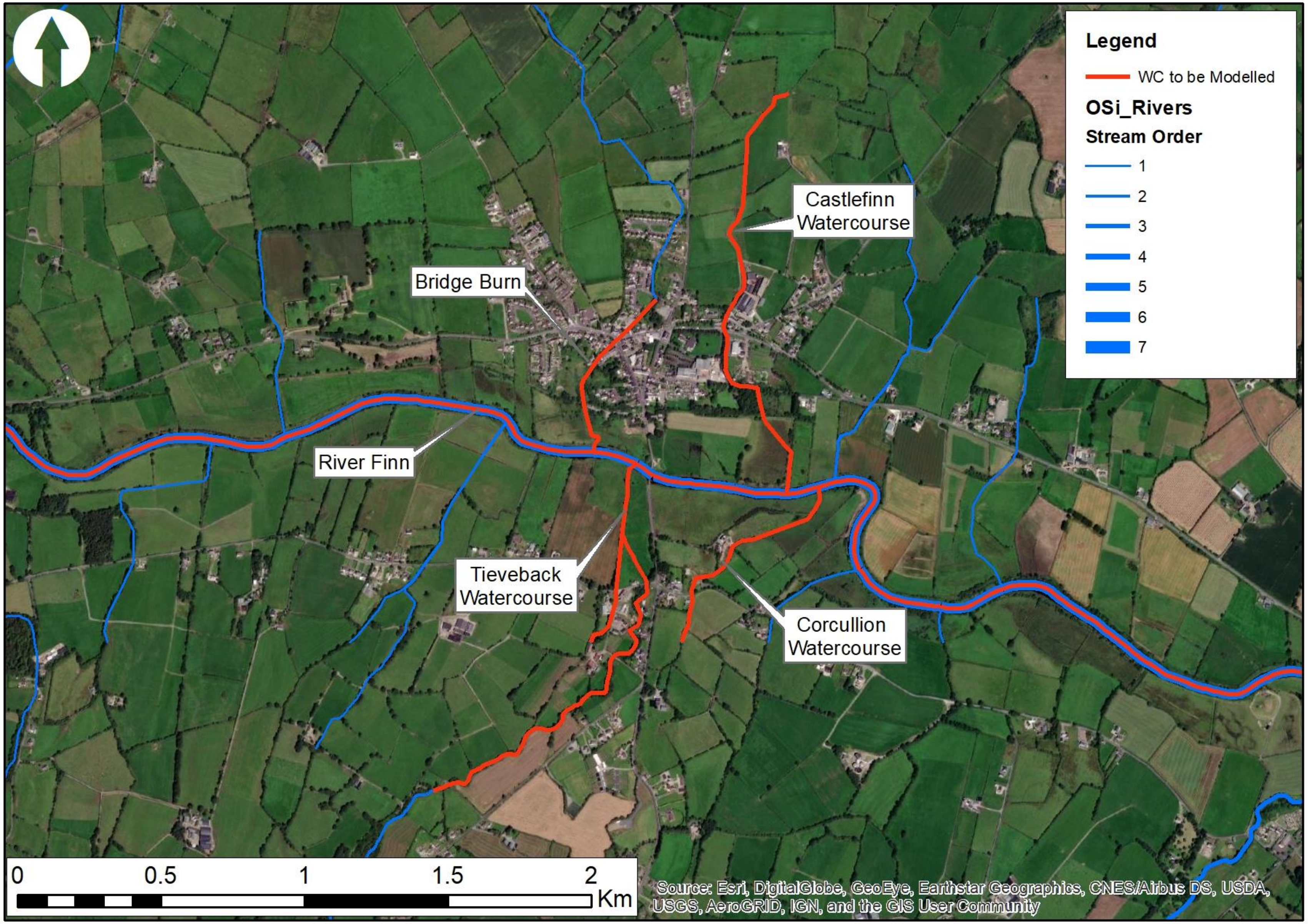


**Figure 1.2 Castlefinn FRS Scheme Area**

## 1.3 Available hydrometric data

There are three hydrometric gauging stations within the Finn Catchment as shown in Figure 1.3. The Office of Public Works (OPW) gauge at Dreenan, downstream of Stranorlar, is located on the River Finn and has a long-term record of water level and some flow data available. However, the gauge was removed in 2004 to facilitate the construction of a new road bridge just downstream. No robust flow data is available for the period up to 2004. The gauge was re-installed in 2010 and RPS carried out a rating review on the station as part of the CFRAM Study from which four years of annual maximum (AMAX) data was processed. However, the rating was calibrated to only a limited number of spot gaugings. The station was decommissioned in 2017.

The Clady Bridge Alert gauging station located downstream of Castlefinn at the village of Clady in Northern Ireland is a water level only gauge which serves to provide a warning of rising water levels at the village.

The main data which will underpin the hydrological analysis is the hydrometric data available on the River Finn at the Ballybofey gauging station operated by the OPW. The gauging station at Ballybofey (Station no.: 01043) has available long-term flood flow data, upstream of Castlefinn.

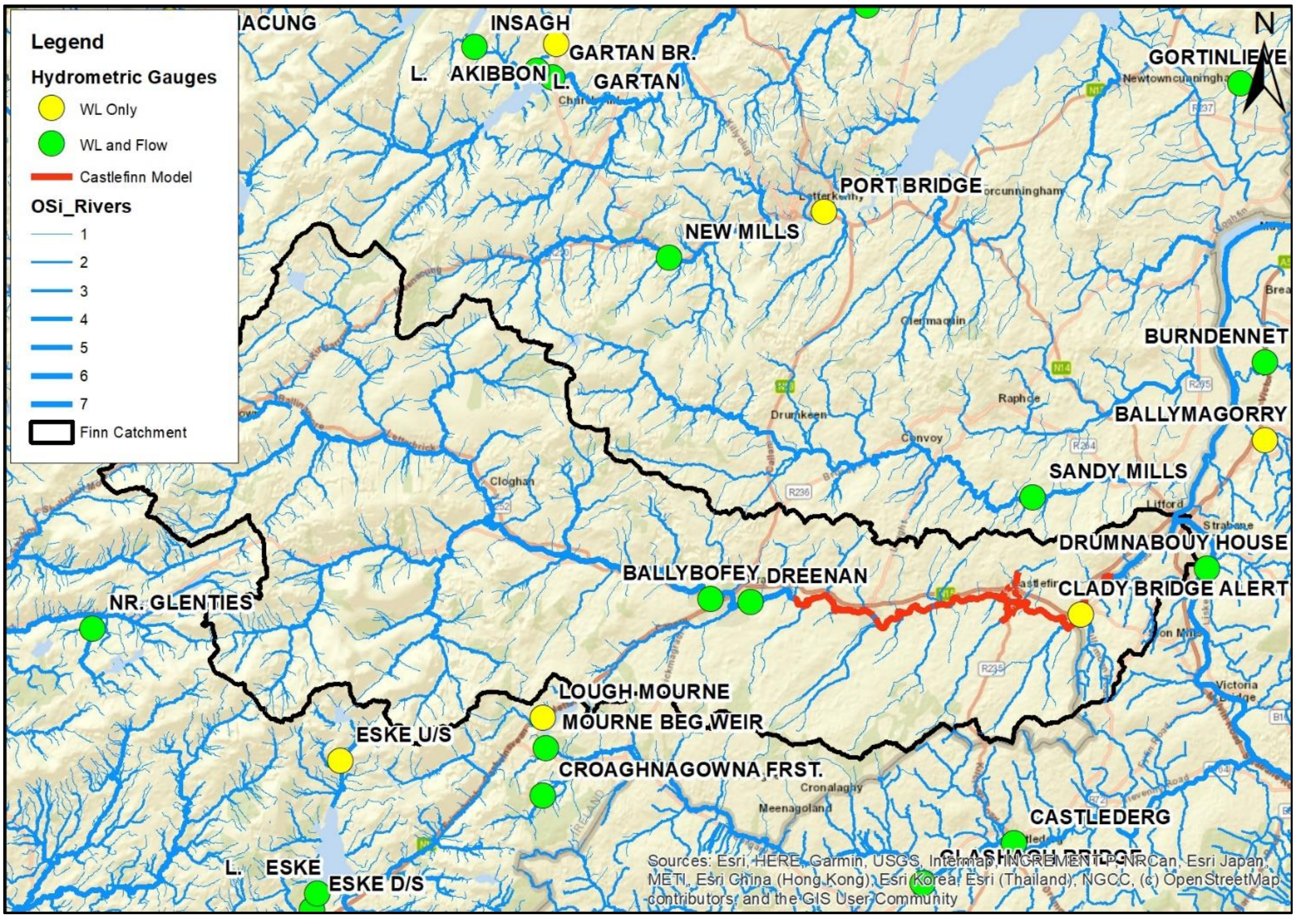


**Figure 1.3 Hydrometric Gauging Stations with data available**

RPS are also engaged in the preparation of the Lifford FRS which includes a rating review of the Ballybofey gauging station based on hydraulic modelling along the River Finn. This rating review aims to provide greater confidence in the flood flow data collected which in turn will inform the design flow estimates on the River Finn at Castlefinn.

There are no hydrometric gauging stations on the tributary watercourses of the River Finn.

**Table 1.1 Hydrometric Gauging station records considered for hydrological analysis**

| Station No. | Station Name | Waterbody | Catch Area $Km^2$ | Operator | Record Start | Record End | Data |
|---|---|---|---|---|---|---|---|
| 01042 | Dreenan | Finn | 353 | OPW | 01/10/1972 | 13/09/2017 | WL & Flow |
| 01043 | Ballybofey | Finn | 319 | OPW | 01/10/1972 | 30/09/2020 | WL & Flow |
| 01041 | Clady Bridge | Finn | 475 | DfI | 11/11/2016 | 30/09/2020 | WL Only |

## 1.4 Flood event history

Recently, the study area has been subject to significant fluvial flooding, most notably in December 2015 (Storm Desmond) and again in August 2017. A summary of the flood history affecting Castlefinn is presented in Table 1.2.

**Table 1.2 Flood History at Castlefinn**

| Event Date | Source | Summary of Reports |
|---|---|---|
| 31st August 2019 | Fluvial | Donegal Daily reported flooding to the bridge at Castlefinn. A video and picture of flooding on the bridge show cars driving through floodwaters on the bridge. |
| 5-6th March 2019 | Fluvial / Pluvial | DonegalLive.ie reported flooding on the night of Tuesday 5th March that impacted areas of Castlefinn town and emanated from the River Finn.<br>There was flooding outside McGlynn's restaurant which prevented the restaurant from opening. |
| 9th Feb 2019 | Fluvial | Donegal Daily reported that there were occurrences of flooding at the Castlefinn Bridge which lead to the area becoming impassable. It is also reported that the Gardaí had to close the Castlefinn Bridge until flood waters receded.<br>There was no other information reported regarding this event. |
| 23rd Aug 2017 | Fluvial / Pluvial | Flood event response data collection recorded the cause of flooding as heavy rainfall leading to flooding from the surface water drainage system.<br>No flooding of properties was recorded, however, the road in front of McGlynns was flooded with the water coming up to the step of the restaurant.<br>It is known that there were extreme flood flows in the Mourne catchment during this event which is likely to have led to backwater effects at Castlefinn.<br>A total length of 230m of the N15 was recorded as flooded. |

| Event Date | Source | Summary of Reports |
|---|---|---|
| 5th Dec 2015 | Fluvial | Flood event response data collection recorded the cause of flooding as overtopping and a tributary (Castlefinn watercourse) overtopping its banks leading to flooding of the area around the Castlefinn Partnership Initiative (CPI) centre. Flooding also occurred around McGlynn's restaurant and was attributed to a combination of prolonged rainfall and high flow in the River Finn preventing the culverted stream adjacent to McGlynn's from draining away causing the stream to back up. Flood water pooled where the N15 dips at the junction to Main street. A total of seven properties were recorded as flooding including:<br>• CPI centre<br>• Youth Club on Lifford Road (N15)<br>• Playschool on Lifford Road (N15)<br>• McGlynn's restaurant<br>• Two residential properties opposite McGlynns<br>• Mechanics garage on Lifford Road (N15)<br>A total length of 1.2km of the N15 was recorded as flooded.<br>A 1.06m flood depth inside the main hall of the CPI centre was recorded.<br>Flood extents are mapped for the event. |
| 15th Nov 2015 | Fluvial | Flood event response data collection recorded the cause of flooding as the River Finn embankments being overtopped near the CPI centre leading to flooding of the ground floor of the centre including the crèche and pharmacy. Flood depths were recorded at 1.2m at the Castlefinn Bridge and 1.7m at Chapel Street.<br>Flood extents are mapped for the event. |
| 25th Oct 2011 | Fluvial / Pluvial | Anecdotal information from www.boards.ie reported that the road from Castlefinn to Ballybofey was badly flooded. It was reported on this website that, in some parts, the side of the road adjacent to the River Finn looked like it had partly collapsed. Castlefinn, Killygordon and Ballybofey were flooded, and a small number of pubs and houses were said to have been affected. However, there is no specific information relating to the location of any flooded properties at Castlefinn and the report is not repeated in any of the news reports. |
| 1st Nov 2009 | Fluvial / Pluvial | It was reported on www.independent.ie that there was flooding across Donegal following the rainfall, leaving a number of minor roads impassable. The east of the county was worst hit, where fire brigade units were called out to assist with flooding in Lifford and Castlefinn. However, no detailed information was available on the extent of the flooding. |
| 28/29th Oct 1989 | Fluvial | It was reported in an article from the Donegal Democrat that one of the worst hit areas in the county was along the River Finn from Castlefinn. The bridge in Castlefinn was impassable for two nights leading to traffic diversions. |

| Event Date | Source | Summary of Reports |
|---|---|---|
| 22nd Oct 1987 | Fluvial | Information on Flood Maps (NI) indicates the extent of flooding which occurred in Castlefinn and Killygordon on 22nd October 1987. Photographs showed the River Finn overflowing and flooding low-lying areas near the river. However, it is not clear what damage was caused during this event in Castlefinn.<br><br>A review of data as part of the Lifford FRS indicates that the flooding during this event was dominated by backwater effects driven mainly by extreme flows in the Mourne catchment backing up through the Finn Valley.<br><br>Rivers Agency has mapped the flood extents for the 1987 event along the Finn to just downstream of Killygordon to Lifford using historical records in the form of oblique aerial photography. |
| 20th/21st Sept 1985 | Fluvial / Coastal | Press articles from the Donegal Democrat state that flooding occurred in Ballybofey/Stranorlar, Bridge End, Buncrana, Castlefinn, Convoy, Donegal, Dungloe, Letterkenny and Lifford on 20th September 1985. The floods were reported as being the worst in living memory by the Chief Fire Officer for Donegal County, speaking to the newspaper. Streams overflowed their banks, and the Finn, Foyle, Eske and Swilly all overflowed their banks at high tide in many locations along their tidal stretches.<br><br>Overflowing streams caused flooding to some houses on Lower Main Street, Castlefinn, where a woman had to be rescued from her flooded home on the opposite side of the bridge at Ringsend. The bridges connecting Liscooley, Carnadore, Castlefinn, Ringsend and Cloughfin-Clady were closed to traffic. |

In addition to the events set out in Table 1.2, there are also reports of recurring flooding at or close to Castlefinn from a meeting with the Electoral Area Engineer for Stranorlar dated 13th January 2006. Locations noted include Liscooley, Castlefinn, Hollow Road and Dunnaloob. The source of flooding is described as either the River Finn or its tributaries and the frequency is noted as ‘every year’.

# 2 FLOOD EVENT ANALYSIS

Developing an understanding of the flood frequency behaviour involves a review of the gauging stations peak flow data. It follows a statistical method known as Extreme Value Analysis (EVA) which aims to estimate the frequency of extreme events based on observed data.

Gauging station peak flow data can be particularly uncertain since it's usually derived from a rating curve (a curve specific to the gauging station which relates the water level in the river (stage height) to estimated discharge). Rating curves are subject to change since the river channel geomorphology (channel dimensions) can be altered over time, particularly after a flood event. The gauging station apparatus itself can also be moved or damaged following large flood events. As a result, regular spot gauging is necessary and rating curves are commonly subject to revision if consecutive spot gaugings appear to diverge from the current rating curve. Spot gauging at times of high flow is difficult and dangerous, notwithstanding the difficulty in predicting the occurrence of a significant event, which is why there are usually limited spot gauge recordings beyond the median annual maximum flood flow ($Q_{med}$). If there are spot gauge recordings at or near the value of $Q_{med}$, then peak flows at the gauge can generally be used to generate reliable estimates of $Q_{med}$. However, flows beyond $Q_{med}$ may be unreliable as the rating equation uses an extrapolated limb where no spot gauge validation exists. These larger flow estimations are therefore particularly uncertain. Nevertheless, peak flow data is still valid for at-site flood frequency estimation since EVA is purely based on the rank of events within the AMAX series, which is much more certain and reliable.

## 2.1 Finn at Ballybofey (01043)

The station further upstream at Ballybofey (01043) is considered to represent the best available flow record on the River Finn. The record extends back to 1972 but the gauging station was moved in August 1992 and there is a large discrepancy in the spread of data between the two record periods. However, for flood frequency estimation and particularly with a view to estimating the frequency of the large events in the 1980s it is worth considering the entire record, but both periods separately, in the at-site analysis.

As part of the Lifford FRS project the rating at Ballybofey was reviewed using hydraulic modelling to first calibrate to spot gauge data and simulate the upper limb rating past the reliable limit (usually dictated by the highest spot gauged flow). A new rating was developed as a result and applied to the period from 2010 onwards as there was uncertainty in applying it before this date. However, for at-site flood frequency analysis, the new rating is applied across the entire record period here. It should be noted that the absolute flow values reported here before 2010 are likely to be incorrect but for at-site flood frequency analysis the application of the latest rating is considered appropriate as consistency, such that events remain within their ranked order, is a primary consideration.

The AMAX based on this rating is shown in Figure 2.1 below. The AMAX series reveals the disparity between record periods. Flood flows, which are derived from the water levels, were recorded frequently exceeding 300$m^3$/s in the earlier record. Conversely, flood flows in excess of a 300$m^3$/s threshold have been observed four times post-1990; in November 2015 which is the largest event on record post-1992 at this location and December 2015 which is not shown on the AMAX graph as it falls within the same hydrological year.

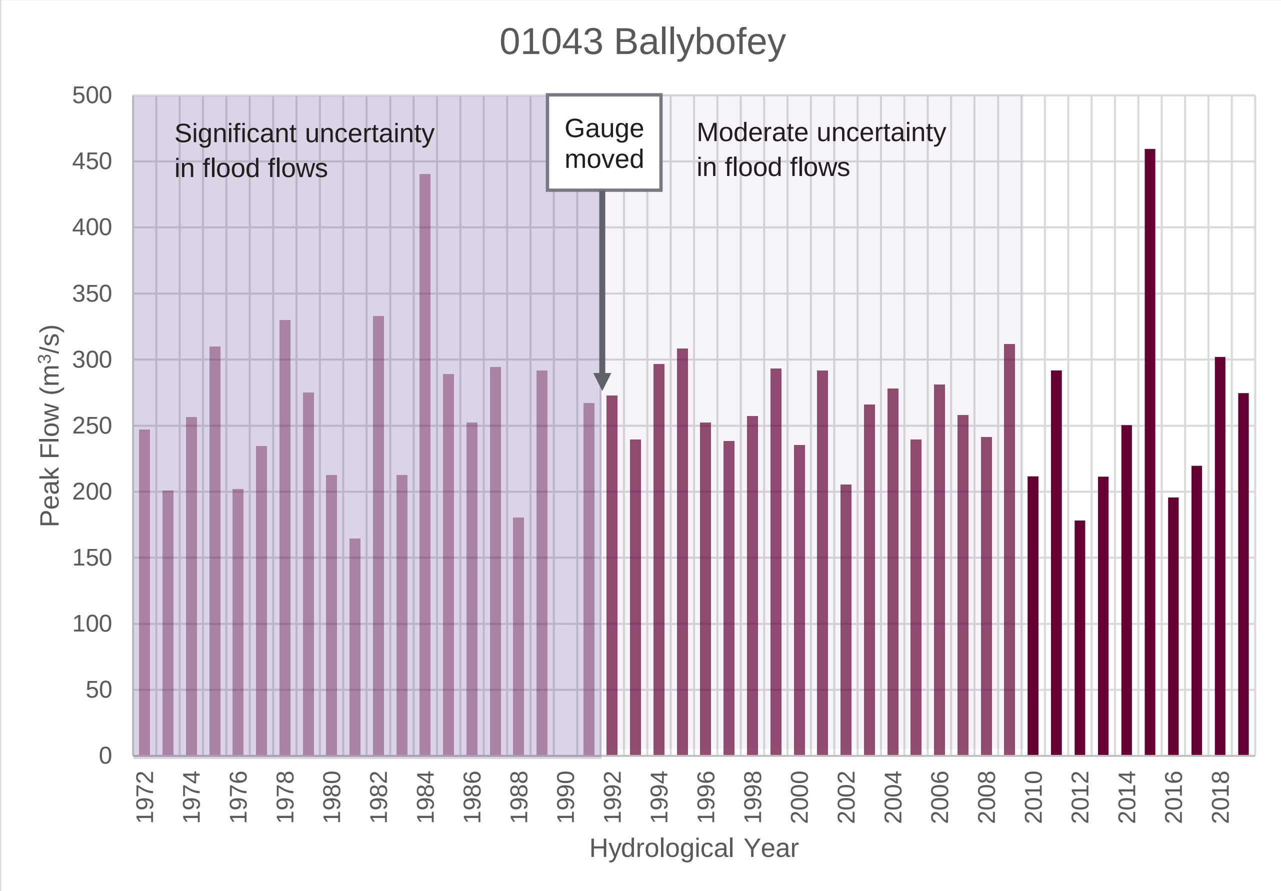


**Figure 2.1 Finn at Ballybofey (01043) – Full AMAX series**

For flood frequency estimation and particularly with a view to estimating the frequency of the large events in the 1980s it is worth considering both periods separately in single site analysis. Common statistical distributions suited to flood frequency behaviour were fitted to the observed data. The resulting flood frequency curves for the periods 1972-1989 and 1991-2019 are presented in Figure 2.2 and Figure 2.3 where the extreme value type I (EV1) and generalised logistic (GLO) distributions provided the best fit to the record periods, respectively.

The EV1 2 parameter distribution provides the best fit to the observed AMAX data for the earlier record period. The largest event in the entire AMAX series occurred in September 1985 and the EVA implies its return period is approximately 45 years. The next two largest events are similar in magnitude with estimated return periods of approximately 7 years.

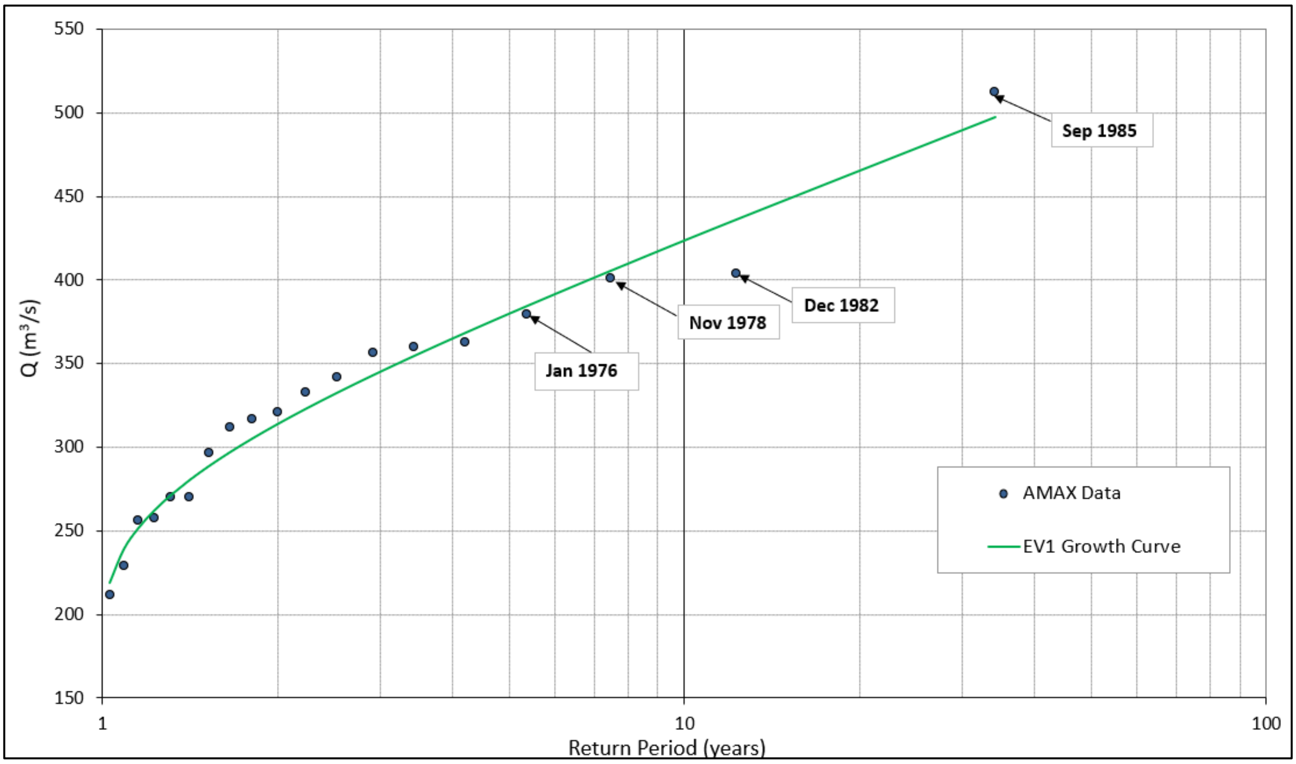


**Figure 2.2 Flood frequency curve fitted to AMAX data (pre-1992) for Finn at Ballybofey (01043)**

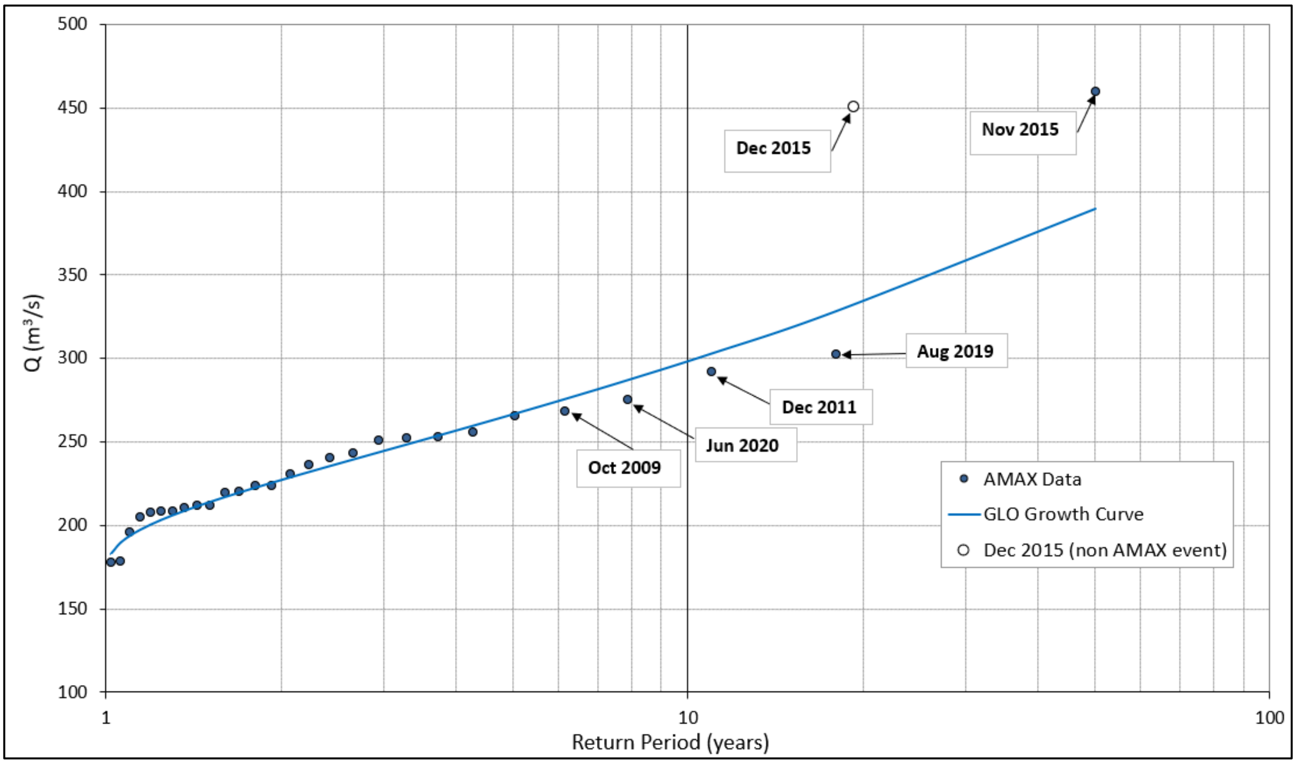


**Figure 2.3 Flood frequency curve fitted to AMAX data (post-1992) for Finn at Ballybofey (01043)**

The GLO 3-parameter distribution provides the best fit to the post-1992 AMAX data although it is a poor fit to the largest event (November 2015) within the record. The December 2015 event is shown within Figure 2.3 but it has not been used in the development of the flood frequency curve as it is not the AMAX event for that year. RPS considered the event within an at-site analysis as if it were from a separate AMAX year for comparative purposes. When it is included the flood frequency curve is steeper and better fitted to the largest event and the estimated return periods based on the GLO distribution are 55 and 51 years respectively for the November and December 2015 events which possibly represents the best true estimate of the return periods for the events. However, given this is outside of best practice the at-site flood frequency curve presented here does not consider the December 2015 event within the analysis and a range of values is presented here (Table 2.1), reflecting the uncertainty from the plotting position of the event to the point at which it intercepts the fitted GLO distribution line.

**Table 2.1 Estimated return period for events at 01043**

| Event Date | Hydrological Year | Peak Flow ($m^3/s$) | Rank | Estimated return period (Years) |
|---|---|---|---|---|
| 31st Aug 2019 | 2018 | 302 | | 10 |
| 5-6th Mar 2019 | 2018 | 130 | | < 1 |
| 9th Feb 2019 | 2018 | 299 | | 10 |
| 23rd Aug 2017 | 2016 | 196 | | 1 - 2 |
| 5th Dec 2015 | 2015 | 451 | 2 | 18 – 100* |
| 15th Nov 2015 | 2015 | 460 | 1 | 51 – 110* |
| 25th Oct 2011 | 2011 | 165 | | < 1 |
| 1st Nov 2009 | 2009 | 139 | | < 1 |
| 28th Oct 2000 | 2000 | 191 | | 1 - 2 |
| 22nd Oct 1987 | 1987 | ***328*** | | 2 - 3 |
| 20th/21st Sept 1985 | 1984 | ***512*** | 3 | 34 – 45* |

*Peak flows marked in* ***bold italics*** *to be treated with caution. Derived using Lifford FRS rating review which has not been modelled or calibrated to pre-1992 data.*

**Return period estimate to be treated with caution (record length < T years). A range of estimated return periods has been presented, representing the flow value as fitted to the GLO distribution for the event in question and the actual plotting position of the event in terms of the return period.*

It should be noted that events in October 1987, December 2015 and August 2017 were large flood events on the River Mourne as recorded upstream of Strabane at the DfI flow gauge at Drumnabuoy House. As the largest tributary of the River Foyle these events represent drivers for flood conditions at Castlefinn which is known to be affected by backwater from flood events in the Foyle at Lifford / Strabane.

## 2.2 Rainfall Analysis

A number of events within the flood history at Castlefinn (Table 1.2) are noted as potentially pluvial flood events and based on the analysis of the Finn flow records (Table 2.1) do not appear to be fluvially driven by peak flows in the River Finn. A summary of the daily rainfall sums at Killygordon (Ballyarrell) station (4.15km west of Castlefinn) which fell on these dates and the associated FSU-derived return period is shown in Table 2.2.

**Table 2.2 Estimated Rainfall Return Period for Pluvial Events**

| Event Date | Daily Rainfall Recorded at Killygordon (Ballyarrell) (mm) | FSU DDF Estimated Rainfall Return Period (Years) |
|---|---|---|
| 5-6th Mar 2019 | 27.9 | <1 year |
| 23rd Aug 2017 | 39.8 | 3 years |
| 25th Oct 2011 | 37.2 | 2 years |
| 1st Nov 2009 | 19.5 | <1 year |

# 3 DESIGN FLOW ESTIMATION

The design flow estimation process entails reviewing all available/useable hydrological data and employing FSU techniques to derive estimates of peak flows across the range of return periods at various locations across the modelled watercourses within the Castlefinn study area.

The techniques employed in Castlefinn for the River Finn are anchored to the hydrometric data at Ballybofey and for the tributaries a range of nearby, hydrological sites have been considered in an attempt to adjust the catchment descriptor-based estimates to relevant local data.

## 3.1 HEP Physical Catchment Descriptors

A detailed hydrological analysis was undertaken to determine the flood flow hydrographs and peak flows for the Castlefinn study area. The design flow estimation requires a comprehensive understanding of the physical catchment characteristics throughout the catchment. Hydrological Estimation Points (HEPs) have been specified at the locations at which design peak flows will be estimated.

HEPs have been established at the most upstream and downstream extremities of the Castlefinn model i.e., at the Ballybofey gauging station and at the bottom of the Finn Valley where the Castlefinn hydraulic model meets the Lifford FRS hydraulic model. There are also intermediate HEPs along the main channel to fully capture the flood flow estimation as the catchment land use and physical characteristics change moving from the rural upstream areas around Fintown and the Bluestack Mountains to the flatter, partially urbanised Finn valley. The intermediate HEPs act as checkpoints along the modelled River Finn to ensure that the hydraulic model is anchored to the hydrological analysis. Tributary HEPs have been specified at the upstream and downstream model extents of four tributary watercourses which flow through the scheme area, two to the north of the Finn flowing through the town and two to the south of the Finn.

The specification of HEPs is presented in Figure 3.1. Table 3.1 details the physical catchment descriptors (PCDs) assigned to each HEP to describe the catchment characteristics moving through the Castlefinn study area.

PCDs used in this project have been updated from the FSU-defined PCDs. The extent of urbanisation (URBEXT), drainage density (DRAIND) and mean average slope (S1085) were updated for each sub-catchment. DRAIND was re-calculated following the review of the catchment delineation. S1085 was re-calculated using the LiDAR coverage for the Finn Valley that was meshed with the 5m National Digital Height Model (NDHM) for the Castlefinn study area. Finally, a PCD which can significantly influence the hydrological analysis is URBEXT. This was updated from the CFRAM Study through an analysis of the most up-to-date CORINE Land Use Mapping. This allowed the URBEXT PCD to be updated to capture the most recent changes in urban extent in the Castlefinn study area, particularly around Castlefinn town. A site visit to Castlefinn to further investigate the course and extent of the Castlefinn watercourse led to significant alterations to the delineated catchment of this watercourse. The site walkover found the OSi river network shapefile to be incorrect and the catchment to be substantially smaller than that indicated by the OSi river network and FSU catchment leading to substantial adjustment (reduction) of the design flow estimation (see Section 3.3.5 for further detail).

Reporting nodes can be added post modelling instead of HEPs if required.

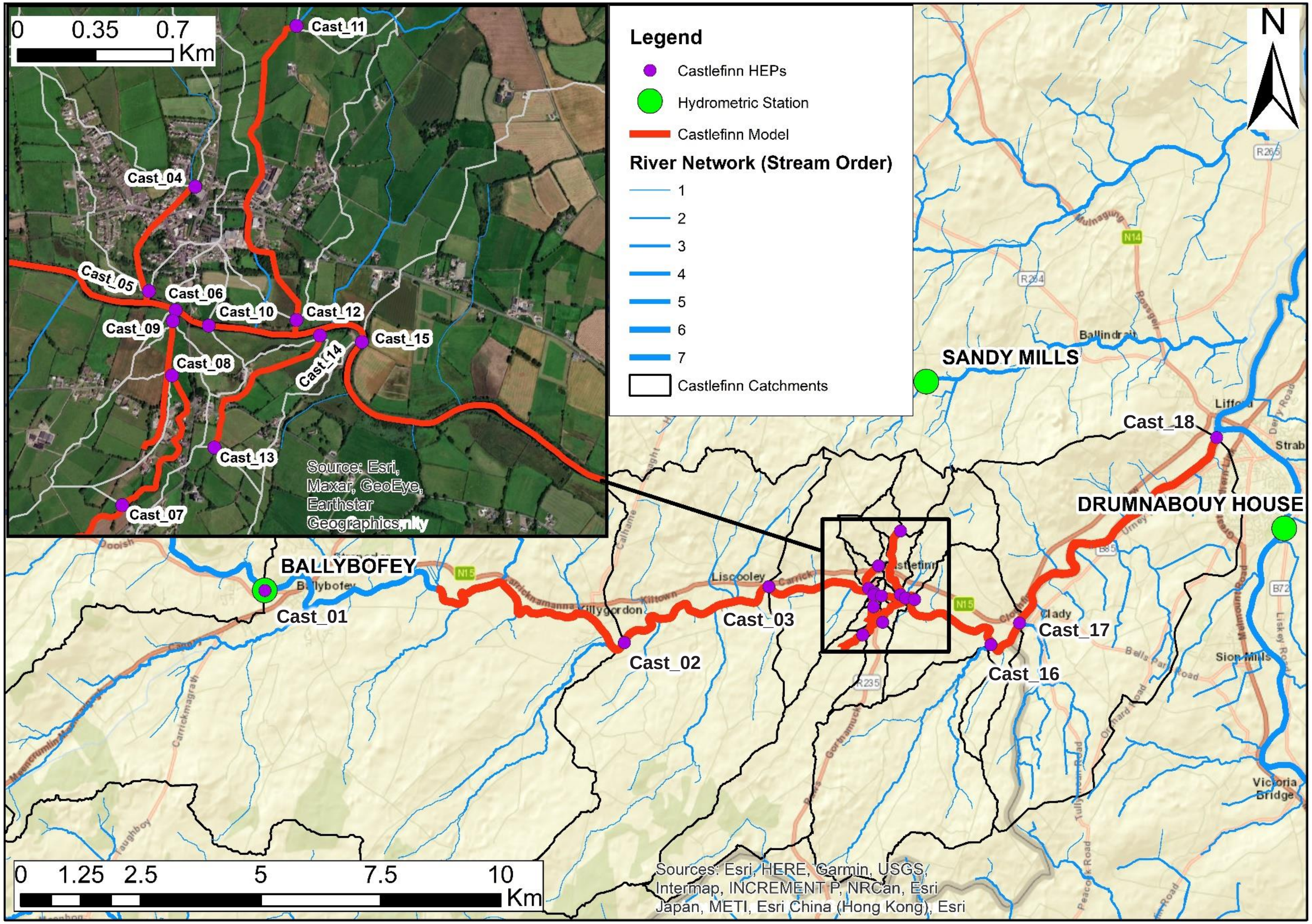


**Figure 3.1 Location of HEPs**

**Table 3.1 Physical Catchment Descriptors for Castlefinn**

| HEP | Location (EPA Name) | Area ($km^2$) | Centroid X | Centroid Y | SAAR (mm) | FARL | $BFI_{SOIL}$ | URBEXT (%) |
|---|---|---|---|---|---|---|---|---|
| CAST_01 | River Finn | 313.98 | 600457 | 898816 | 1988 | 0.964 | 0.297 | 0.1 |
| CAST_02 | River Finn | 401.30 | 603685 | 897649 | 1841 | 0.970 | 0.322 | 0.9 |
| CAST_03 | River Finn | 433.27 | 604846 | 897339 | 1789 | 0.972 | 0.329 | 0.8 |
| CAST_04 | N.W. Tributary (Bridge Burn Stream) | 0.62 | 625789 | 896930 | 1059 | 1.000 | 0.575 | 0.0 |
| CAST_05 | N.W. Tributary (Bridge Burn Stream) | 1.01 | 625859 | 896420 | 1062 | 1.000 | 0.589 | 8.7 |
| CAST_06 | River Finn | 441.05 | 605390 | 897269 | 1781 | 0.972 | 0.330 | 1.6 |
| CAST_07 | S.W. Tributary (Tieveback) | 7.48 | 623927 | 890673 | 1110 | 1.000 | 0.348 | 0.0 |
| CAST_08 | S.W. Tributary (Tieveback) | 0.15 | 625917 | 894068 | 1107 | 1.000 | 0.370 | 0.0 |
| CAST_09 | S.W. Tributary (Tieveback) | 7.80 | 624029 | 890839 | 1107 | 1.000 | 0.370 | 0.0 |
| CAST_10 | River Finn | 448.97 | 605719 | 897157 | 1781 | 0.972 | 0.330 | 1.6 |
| CAST_11 | N.E. Tributary (Castlefinn) | 1.34 | 627650 | 896445 | 1059 | 1.000 | 0.575 | 0.0 |
| CAST_12 | N.E. Tributary (Castlefinn) | 2.38 | 627382 | 896274 | 1062 | 1.000 | 0.589 | 5.9 |
| CAST_13 | S.E. Tributary (Corcullion) | 0.99 | 626067 | 892944 | 1078 | 1.000 | 0.505 | 0.0 |
| CAST_14 | S.E. Tributary (Corcullion) | 1.17 | 626147 | 893149 | 1078 | 1.000 | 0.506 | 0.0 |
| CAST_15 | River Finn | 455.12 | 606783 | 896934 | 1781 | 0.973 | 0.331 | 2.3 |
| CAST_16 | Dresnagh Tributary | 12.25 | 628671 | 893530 | 1087 | 1.000 | 0.509 | 0.6 |
| CAST_17 | River Finn | 473.79 | 607960 | 896815 | 1731 | 0.974 | 0.334 | 3.8 |
| CAST_18 | River Finn | 502.30 | 608299 | 896797 | 1730 | 0.976 | 0.334 | 3.8 |

Where;
FARL – *Index of flood attenuation by reservoirs and lakes;*
SAAR – *Standard-period average annual rainfall (mm);*
URBEXT – *Proportional extent of catchment area mapped as urbanised;*
AREA – *Individual area of each catchment computed based on GIS-based catchment delineation ($km^2$)*;
$BFI_{SOIL}$ – *Soil Base Flow index (estimate of BFI derived from soils, geology, and climate data).*

## 3.2 Index Flood Flow ($Q_{med}$) Estimation

The first step in determining the design flows is the estimation of the Index Flood Flow ($Q_{med}$) at each HEP. The Index Flood Flow is a crucial flood statistic as it can be robustly determined from suitable gauged locations with a significant record length (more than seven years).

The Ballybofey hydrometric gauging station is the most upstream HEP on the River Finn for the Castlefinn FRS model. Therefore, gauged data and observed $Q_{med}$ is available in the upstream extents of the analysis. This allows for observed hydrometric data to anchor the hydrological analysis to the hydraulic model. Estimation of $Q_{med}$ using the gauged method under FSU was adopted along the River Finn main channel.

In estimating $Q_{med}$ in the tributaries surrounding Castlefinn town centre, there is no observed $Q_{med}$ available. Therefore, in these tributary reaches the ungauged approach under FSU to estimate $Q_{med}$ is adopted with an appropriate 'pivotal site' selected to provide an adjustment.

### 3.2.1 $Q_{med}$ at Gauged Locations

Table 3.2 shows the observed $Q_{med}$ and the available record period for hydrometric data at the Ballybofey gauging station.

**Table 3.2 Observed $Q_{med}$ at Ballybofey gauging station**

| River | Gauge Location | Number | $Q_{med}$ ($m^3/s$) | $Q_{med}$ Record Period |
|---|---|---|---|---|
| Finn | Ballybofey | 01043 | **257.9** | 1991 – 2019<br>(Hydrological years) |

The Ballybofey gauging station represents a robust estimation of $Q_{med}$ in the River Finn since the gauging station was subject to a rating review as part of the Lifford FRS hydrology analysis[1]. This has increased the confidence in the rating at the gauging station at higher flows and has validated the observed $Q_{med}$ to be used during this hydrological analysis at Castlefinn to provide pivotal site adjustment of ungauged estimates.

### 3.2.2 $Q_{med}$ at ungauged locations

While the inflow to the Castlefinn hydraulic model is located at the Ballybofey gauging station, estimation of $Q_{med}$ is required moving downstream for all HEPs in the study area. Estimation of $Q_{med}$ on both the River Finn and the tributary watercourses was initially conducted using ungauged methods. This involves the estimation of $Q_{med}$ in its rural form, referred to henceforth as $Q_{med\ rural}$, which is based on the FSU methods for ungauged catchments, i.e., using regression equations derived from FSU Work Package 2.3 and for the smaller catchments from FSU Work Package 4.2. Other methods for estimating flood flows in smaller catchments have been considered. These include IH124, ADAS, Rationale Method, and the FSU 5 variable equation. The FSU 5 Variable equation is the preferred small catchment method for this analysis. The other methods presented are derived from lower resolution and outdated datasets compared to FSU. FSU Work Package 4.2 concluded that the FSU 5 Variable equation has the lowest factorial standard error when compared to these other methods on Irish small catchments. The other methods have therefore been discounted.

The FSU 5 Variable equation has also been applied as the preferred method for $Q_{med}$ estimation in smaller catchments. These methods are not applied to the River Finn HEPs but the small watercourses and drains that flow through Castlefinn town centre where there is the greatest uncertainty in the flow estimation. The outputs of both methods are compared and that deemed most appropriate has been carried forward for design flow estimation.

[1] Lifford Hydrology Report (2022) Available at: http://liffordfrs.ie/#

FSU 7 Variable (standard method):

$$Q_{med\ rural} = 1.237*l0^{-5}*AREA^{0\cdot937}*BFI_{SOIL}{}^{-0.922}*SAAR^{1.306}*FARL^{2\cdot217}*DRAIND^{0.341}*S1085^{0\cdot185}*(1+ARTDRAIN2)^{0.408}$$

FSU 5 Variable (small catchments):

$$Q_{med\ rural} = 2.0951*10^{-5}*AREA^{0\cdot9245}*BFI_{SOIL}{}^{-0.9030}*SAAR^{1.2695}*FARL^{2\cdot3163}*S1085^{0\cdot2513}$$

While the FSU 5 variable equation will not be used on the River Finn main channel, both methods were interrogated on the tributary reaches at Castlefinn to compare the outputs of both methods.

### 3.2.3 Pivotal Site Adjustment

FSU recommends that the ungauged $Q_{med}$ estimates (i.e., $Q_{med\ rural}$) are adjusted using a 'pivotal site'; a geographically close or hydrologically similar gauged catchment that can be used to reduce the error and level of uncertainty in the estimates. The basis of this adjustment is grounded in the fact that $Q_{med}$ estimation based purely on the physical catchment descriptor regression equations can be highly uncertain as it has been generalised for application across a wide range of catchments nationally.

However, this estimation can be improved, and the uncertainty reduced by using data transfer methods from other nearby or hydrologically similar gauged catchments. This approach borrows observed flood flow data from an appropriately gauged subject catchment, which is known as a 'pivotal site' in FSU methodologies.

A comprehensive review of nearby and hydrologically similar gauging stations was conducted in relation to the Castlefinn study area. At the time of the CFRAM Study, the Ballybofey gauging station on the River Finn was used as a pivotal site adjustment for the River Finn affecting Castlefinn. Following the rating review carried out as part of the Lifford FRS there is greater certainty in the observed $Q_{med}$ value at the Ballybofey station, and hence the pivotal site adjustment factor. It is the obvious choice for pivotal site adjustment of the River Finn reaches affecting Castlefinn.

The adjustment is considered in relation to the catchments in their rural state such that the effects of urbanisation from the pivotal site are not transferred. In light of this, the estimated effect of urbanisation may need to be stripped from the observed $Q_{med}$ value by dividing the observed value by the UAF. However, in the case of the Ballybofey station, urbanisation is less than 1% and is not considered to have any significant effect on the observed $Q_{med}$ value. The observed and FSU7 variable equation predicted $Q_{med}$ values, and the resulting pivotal site adjustment factor is shown in Table 3.3.

**Table 3.3 Pivotal Site Adjustment Factors (AdjFacs) for River Finn**

| River | Gauge Location | Number | $Q_{med}$ Observed ($m^3/s$) | $Q_{med\ rural}$ Predicted ($m^3/s$) | Adjustment Factor (AdjFac) |
|---|---|---|---|---|---|
| Finn | Ballybofey | 01043 | 257.9 | 256.0 | **1.01** |

Table 3.3 suggests that the FSU 7 variable catchment descriptor equation is performing well for the River Finn main channel. Essentially this suggests that the $Q_{med\ rural}$ estimates require an approximately 1% uplift given an adjustment factor of 1.01.

However, there is uncertainty in applying this adjustment factor to the smaller, tributary watercourses affecting Castlefinn. The use of the Ballybofey gauging station as a pivotal site for the tributary watercourses given it is the only potential pivotal site available within the Finn catchment would seem appropriate. However, the catchment that this gauging station represents is significantly larger, wetter, and more upland than the smaller, tributary catchments that affect Castlefinn.

A further review of available small catchment hydrometric gauging stations which were appropriate for use as a pivotal site for the tributaries was conducted. This review identified a relatively new gauging station operated by the Environmental Protection Agency (EPA); Gortinlieve at Carrigans (Station No.: 01016) as the most appropriate pivotal site for the tributaries. This gauging station is located on a small tributary of the River Foyle. The station is operational since 2010 with 11 years of continuous data available. The station was not available at the time of FSU, nor did it have sufficient data at the time of the CFRAM Study. Although the highest gauged flow is significantly lower than the $Q_{med}$ value, the gauge is contained within a concrete channel with a flat V-weir providing the control. The high flow rating is described as excellent by the EPA and RPS has deemed it suitable for $Q_{med}$. The catchment is one of the closest stations to the tributary catchments with the other closer sites representing much larger catchments and therefore lower hydrological similarity. The Gortinlieve station has a fairly high hydrological similarity to all of the tributary catchments. The Gortinlieve station has therefore been taken forward as the chosen pivotal site for $Q_{med}$ adjustment for all of the tributary catchment HEPs based on hydrological similarity and geographical closeness. A summary of the main tributary catchment descriptors with the Gortinlieve gauged catchment descriptors is shown below.

**Table 3.4 Comparison of Tributary and Gortinlieve GS Catchment Descriptors**

| HEP | Location (EPA Name) | Area ($km^2$) | SAAR (mm) | FARL | $BFI_{SOIL}$ | S1085 (m/km) | URBEXT (%) |
|---|---|---|---|---|---|---|---|
| CAST_05 | N.W. Tributary (Bridge Burn Stream) | 1.01 | 1062 | 1.00 | 0.589 | 11.17 | 8.7 |
| CAST_09 | S.W. Tributary (Tieveback) | 7.80 | 1107 | 1.0 | 0.370 | 15.54 | 0.0 |
| CAST_12 | N.E. Tributary (Castlefinn) | 2.38 | 1062 | 1.00 | 0.589 | 11.169 | 5.6 |
| CAST_14 | S.E. Tributary (Corcullion) | 1.17 | 1078 | 1.00 | 0.506 | 10.33 | 0.0 |
| CAST_16 | Dresnagh Tributary | 12.25 | 1087 | 1.00 | 0.509 | 21.73 | 0.6 |
| **Gortinlieve GS** | **Carrigans** | **0.958** | **1042** | **1.00** | **0.346** | **75.07** | **0.0** |

Table 3.5 illustrates the observed and predicted $Q_{med}$ values and the resulting pivotal site adjustment factor for the Gortinlieve at Carrigans gauging station.

**Table 3.5 Pivotal Site Adjustment Factor (AdjFacs), Gortinlieve at Carrigans (01016)**

| River | Gauge Location | Number | $Q_{med}$ Observed ($m^3/s$) | $Q_{med\ rural}$ FSU7 Predicted ($m^3/s$) | $Q_{med\ rural}$ FSU5 Predicted ($m^3/s$) | FSU7 Adjustment Factor (AdjFac) | FSU5 Adjustment Factor (AdjFac) |
|---|---|---|---|---|---|---|---|
| Carrigans | Gortinlieve | 01016 | 0.910 | 0.596 | 1.054 | 1.527 | 0.864 |

Table 3.5 suggests that the FSU 7 variable equation is significantly underestimating $Q_{med}$ by approximately 53%. Conversely, the FSU 5 variable equation is suggested to be overestimating $Q_{med}$ by approximately 14%. The FSU 5 variable equation estimate of $Q_{med\ rural}$ was used with the observed $Q_{med}$ at Gortinlieve as the basis of the pivotal site adjustment of $Q_{med}$ on the ungauged tributary catchments affecting Castlefinn. The FSU 5 variable estimate was considered more appropriate given the small nature of the catchments, the uncertainty in the drainage-related catchment descriptors (i.e., drainage density DRAIND) and the fact that this method at the small catchment scale was found to have produced lower statistical error within FSU Work Package 4.2 than the FSU 7 variable equation.

## 3.2.4 Urban Adjustment

This $Q_{med\ rural}$ value does not consider the effects of urbanisation which is considered separately through an Urban Adjustment Factor calculated as follows:

$$\mathbf{UAF = (1+URBEXT)^{1.482}}$$

The final $Q_{med}$ which considers the effect of urbanisation is then calculated:

$$\mathbf{Q_{med\ urban} = UAF^{*}\ Q_{med\ rural}}$$

The urban adjustment was not applied to River Finn main channel reaches as the main channel as the level of urbanisation in the Finn catchment is considered to be sufficiently low (<1%) as to have a negligible effect on peak flows in the River Finn.

However, the urban adjustment has been applied to the small tributary watercourses that affect Castlefinn. In general, the urban adjustment has been applied where the level of urbanisation is deemed to have a potential impact on run-off and the peak design flows within the catchment i.e., any tributary catchment that has an URBEXT value of greater than 2.5% (0.025) has had the urban adjustment factor applied.

Table 3.6 illustrates the tributary catchments affecting Castlefinn and the effect of the urban adjustment on the rural, catchment descriptor based (FSU 5 variable) $Q_{med}$.

**Table 3.6 Urban Adjustment to Tributary Catchment Rural (FSU 5) Qmed values**

| HEP | Location | Area ($km^2$) | $Q_{med\ rural}$ ($m^3/s$) | URBEXT % | Urban Adjustment Factor | $Q_{med\ urban}$ ($m^3/s$) |
|---|---|---|---|---|---|---|
| CAST_04 | N.W. Tributary (Bridge Burn Stream) | 0.62 | 0.310 | 0 | 1.00 | 0.310 |
| CAST_05 | N.W. Tributary (Bridge Burn Stream) | 1.01 | 0.434 | 8.7 | **1.13** | **0.491** |
| CAST_07 | S.W. Tributary (Tieveback) | 7.48 | 4.885 | 0 | 1.00 | 4.885 |
| CAST_08 | S.W. Tributary (Tieveback) | 0.15 | 0.130 | 0 | 1.00 | 0.130 |
| CAST_09 | S.W. Tributary (Tieveback) | 7.8 | 5.010 | 0 | 1.00 | 5.010 |
| CAST_11 | N.E. Tributary (Castlefinn) | 1.34 | 0.633 | 0 | 1.00 | 0.633 |
| CAST_12 | N.E. Tributary (Castlefinn) | 2.38 | 0.958 | 5.9 | **1.089** | **1.043** |

| HEP | Location | Area ($km^2$) | $Q_{med\ rural}$ ($m^3/s$) | URBEXT % | Urban Adjustment Factor | $Q_{med\ urban}$ ($m^3/s$) |
|---|---|---|---|---|---|---|
| CAST_13 | S.E. Tributary (Corcullion) | 0.99 | 0.513 | 0 | 1.00 | 0.513 |
| CAST_14 | S.E. Tributary (Corcullion) | 1.17 | 0.571 | 0 | 1.00 | 0.571 |
| CAST_16 | Dresnagh Tributary | 12.25 | 6.064 | 0.6 | **1.01** | **6.114** |

The urban adjustment has been applied to those tributary catchments affecting Castlefinn to represent the impact of increasing urbanisation and impervious surfaces as the $Q_{med}$ estimation process moves into the Castlefinn town centre.

## 3.3 Growth Curve Development

### 3.3.1 Previous studies

Growth curve development was previously undertaken as part of the NWNB CFRAM Study[2] based on the FSU methodologies to determine growth factors for a range of design events. The growth factors from the NWNB CFRAM Study are presented in Table 3.7, where AEP is the Annual Exceedance Probability.

**Table 3.7 NWNB CFRAM Study Growth Factors**

| Watercourse | 50% AEP | 20% AEP | 10% AEP | 5% AEP | 2% AEP | 1% AEP | 0.5% AEP | 0.1% AEP |
|---|---|---|---|---|---|---|---|---|
| River Finn | 1.00 | 1.25 | 1.43 | 1.62 | 1.90 | 2.15 | 2.42 | 3.20 |
| Tributaries | 1.00 | 1.30 | 1.52 | 1.76 | 2.14 | 2.47 | 2.86 | 4.02 |

### 3.3.2 At Site Growth Curves

The single site analyses in Chapter 2 estimated the flood frequency curve based solely on the Ballybofey gauging station record. The growth curves are extracted from the flood frequency curves by taking the ratio of estimated peak flow - at each return period of interest - to the observed $Q_{med}$ value. A plot of the at-site-based growth factors, using the best-fitted GLO distribution, is shown in Figure 3.2 based on the latter record period (1992 – 2020).

[2] Extracted from the North Western UoM01 Hydrology Report available at: https://s3-eu-west-1.amazonaws.com/docs.floodinfo.opw/floodinfo_docs/NWNB_CFRAM/_UOM_01/01_Hydrology/IBE0700Rp0006_UoM01_Hydrology_Report_F03.pdf

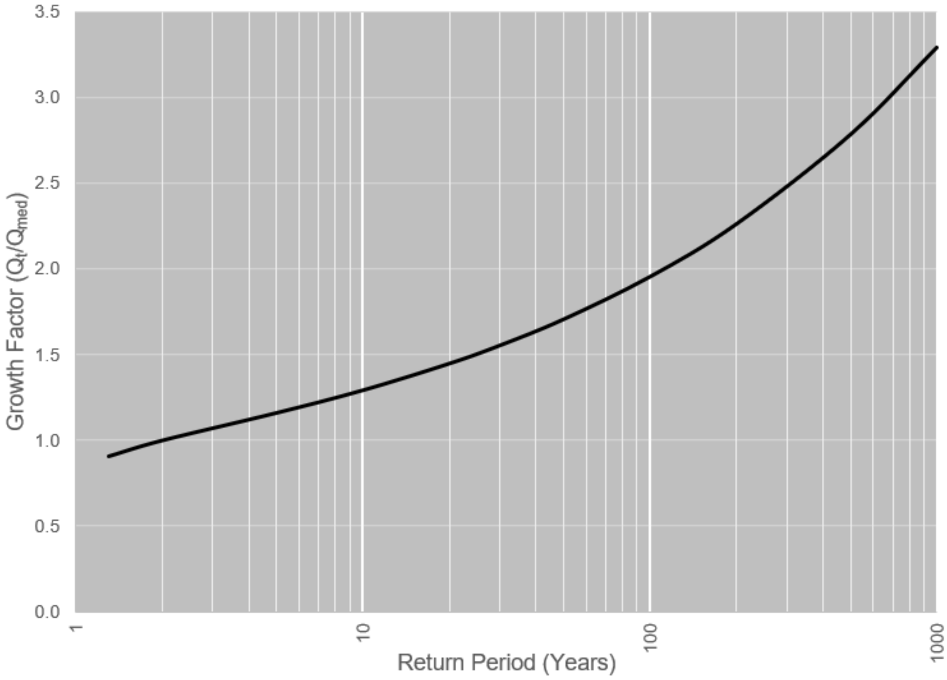


**Figure 3.2 At-Site Growth Curve at Ballybofey (01043)**

The at-site growth curve results in a similar, but slightly flatter growth curve / lower growth factors than the CFRAM Study.

The at-site growth curve developed for Ballybofey is based on 28 years of Annual Maxima (AMAX) flood data. Following the rating review, the AMAX values are considered to be robust, and the flood frequency curve is suitable for the basis of flood flow estimation.

As noted in the table below, adapted from FEH Volume 3, Tables 8.2 and 8.3, it is only recommended that at-site analysis is used as the basis for design flow estimation if there are more than T years of AMAX data, where T is the design return period. In other words, the Ballybofey at-site analysis is only recommended for use as the basis for design flow estimation up to 49 years, (i.e., for 50% AEP, 20% AEP, 10 AEP and 5% AEP).

**Table 3.8 Selection of At-Site or Pooled Growth Factors / Curves**

| Record Length | At-Site Analysis | Pooled Analysis | Preferred Method |
|---|---|---|---|
| < T/2 or 14 years | No | Yes | Pooled |
| T/2 to T years | For confirmation | Yes | Pooled |
| T to 2T years | Yes | Yes | Joint |
| > 2T years | Yes | For confirmation | At-Site |

### 3.3.3 Development of Pooled Growth Curves

Pooled growth curves were developed at selected HEPs representing the main sub-catchments in the study area. This includes upstream and downstream of Castlefinn on the River Finn (CAST_03 & CAST_18) and for each of the four modelled tributaries (CAST_05, CAST_09, CAST_12 and CAST_14). The pooling groups developed for the Castlefinn FRS were based on the original FSU dataset (up to 2004) which was then enhanced/updated with the addition of:

- Hydrological similar gauge records from Northern Ireland
- Updated station AMAX years for sites found to be hydrologically similar (i.e., within the pooling groups following initial selection). This update was applied to FSU sites which have recently been determined to be robust for pooling group analysis by the OPW. This was to ensure the updated pooled analysis included the most recent, robust hydrometric data to inform the development of new growth curves. FSU sites not included within the list were assumed to be robust up to 2004 (as per the original FSU classification) and were retained.

For most stations, this meant that AMAX years were updated to 2019 or 2020.

The pooling groups were reviewed and adapted in line with FSU guidance. The pooled approach was applied at the HEPs discussed on the main watercourses to achieve a pooling group of at least 500 AMAX years of data, representing 5T years (5 x the target return period, T, which is taken as the design standard of protection of 100 years). The final pooled stations for each site are provided in Table 3.9.

**Table 3.9 Sites included within Pooling Groups**

| CAST_03 | CAST_05 | CAST_09 | CAST_12 | CAST_14 | CAST_18 |
|---|---|---|---|---|---|
| 01043 - Ballybofey | 06030 - Ballygoly | 36021 - Kiltybardan | 06030 - Ballygoly | 09011 - Frankfort | 1043 - Ballybofey |
| 18050 - Duarrigle | 25034 - Rochfort | 23012 - Ballymullen | 25034 - Rochfort | 06030 - Ballygoly | 18050 - Duarrigle |
| 34007 - Ballycarroon | 09011 - Frankfort | 27001 - Inch Br. | 09011 - Frankfort | 25034 - Rochfort | 34007 - Ballycarroon |
| 38001 - Clonconwal Ford | 30020 - Ballyhaunis | 05020 - Enler at Comber | 30020 - Ballyhaunis | 30020 - Ballyhaunis | 23002 - Listowel |
| 22006 - Flesk | 10022 - Carrickmines | 05008 - Lagan at Drumiller | 10022 - Carrickmines | 10022 - Carrickmines | 22006 - Flesk |
| 28001 - Ennistimon | 25040 - Roscrea | 08012 - Ballyboghil | 25040 - Roscrea | 25040 - Roscrea | 28001 - Ennistimon |
| 23002 - Listowel | 8005 - Kinsaley Hall | 05005 - Ravernet at Ravernet | 22009 - White Bridge | 08005 - Kinsaley Hall | 39009 - Aghawoney |
| 39009 - Aghawoney | 22009 - White Bridge | 14033 - Mountmellick | 08005 - Kinsaley Hall | 08012 - Ballyboghil | 38001 - Clonconwal Ford |
| 18016 - Duncannon | 16051 - Clobanna | 08007 - Ashbourne | 16051 - Clobanna | 22009 - White Bridge | 34010 - Cloonacannana |
| 34010 - Cloonacannana | 24022 - Hospital | 03028 - Agivey at Whitehall | 24022 - Hospital | 16051 - Clobanna | 18016 - Duncannon |
| 32011 - Louisburg Weir | 06031 - Curralhir | 01041 - Sandy Mills | 06031 - Curralhir | 08007 - Ashbourne | 34029 - Knockadangan |
| 34029 - Knockadangan | 08002 - Naul | 36031 - Lisdarn | 08002 - Naul | 06031 - Curralhir | 32011 - Louisburg Weir |
| 19014 - Dromcarra | 10021 - Common's Road | 32011 - Louisburg Weir | 10021 - Common's Road | 01055 - Mourne Beg Weir | 19014 - Dromcarra |
| 33001 - Glenamoy | 09035 - Killeen Road | 34009 - Curraghbonaun | 09035 - Killeen Road | 08002 - Naul | 2001 -Roe at Ardnargle |
| | 08012 - Ballyboghil | 33001 - Glenamoy | 08012 - Ballyboghil | 24022 - Hospital | |
| | 09002 - Lucan | | 09002 - Lucan | 10021 - Common's Road | |
| | 08007 - Ashbourne | | 13002 - Foulk's Mill | 09035 - Killeen Road | |
| | | | | 10004 - Laragh | |
| | | | | 09002 - Lucan | |

Following the development of the pooling groups, the pooled flood frequency curves were developed with the ‘best fit’ flood-like distributions applied to the pooled L-moments. The resulting pooled flood frequency growth factors and their associated distributions are provided in Table 3.10.

**Table 3.10 HEP Pooled growth factors**

| HEP | Preferred Distribution | 50% AEP | 20% AEP | 10% AEP | 5% AEP | 2% AEP | 1% AEP | 0.5% AEP | 0.1% AEP |
|---|---|---|---|---|---|---|---|---|---|
| **CAST_03** | GEV | 1.00 | 1.32 | 1.54 | 1.75 | 2.02 | 2.23 | 2.44 | 2.93 |
| **CAST_05** | GEV | 1.00 | 1.48 | 1.81 | 2.13 | 2.57 | 2.92 | 3.27 | 4.14 |
| **CAST_09** | GLO | 1.00 | 1.25 | 1.42 | 1.61 | 1.89 | 2.13 | 2.41 | 3.19 |
| **CAST_12** | GLO | 1.00 | 1.39 | 1.66 | 1.95 | 2.37 | 2.72 | 3.12 | 4.24 |
| **CAST_14** | GLO | 1.00 | 1.42 | 1.74 | 2.08 | 2.61 | 3.08 | 3.62 | 5.25 |
| **CAST_18** | GEV | 1.00 | 1.29 | 1.47 | 1.64 | 1.85 | 1.99 | 2.13 | 2.44 |

*Note: Grey cells denote River Finn HEPs*

For the River Finn, it was noted that the generalised extreme value (GEV) 3 parameter distribution was found to be the best fit at both HEPs when considering the L moment ratios (L-CV, L-Skewness and L-Kurtosis) of both the pooling group sites and the various flood-like distributions. This is despite the GLO distribution being found to be the best fit to the at-site Ballybofey data (Figure 3.2) although it should be noted that the difference is marginal between the GLO and GEV distributions.

### 3.3.4 Selection of Final Growth Curves

Following a review of the different growth curves for the two HEPs considered on the River Finn and comparison against the CFRAM Study and at-site Ballybofey analysis, it was decided to generalise the growth factors for the River Finn by taking the average of CAST_03 and CAST_18 and applying across the entire Finn reaches of the study area. A comparison of the growth curves is shown in Figure 3.3.

The averaged River Finn growth curve is more conservative than either the at-site or the CFRAM Study up to the 1% AEP. At the 1% AEP the CFRAM Study growth curve and the averaged River Finn growth curve are well matched resulting in a very similar 1% AEP growth factor (2.11 compared to 2.15 for CFRAM Study). Both the CFRAM Study and the at-site Ballybofey curve result in higher growth factors for the 0.1% AEP. It should be noted that the at-site growth curve is not considered reliable at higher return periods (beyond 50 years) and its use at low return periods could result in underestimated design flows. This is supported by the fact that when the December 2015 event (a non-AMAX event) is included within the at-site analysis it results in a steeper curve.

The average growth curve is taken forward as the basis of design flow estimation as it is derived from the most up-to-date and relevant pooled gauge data.

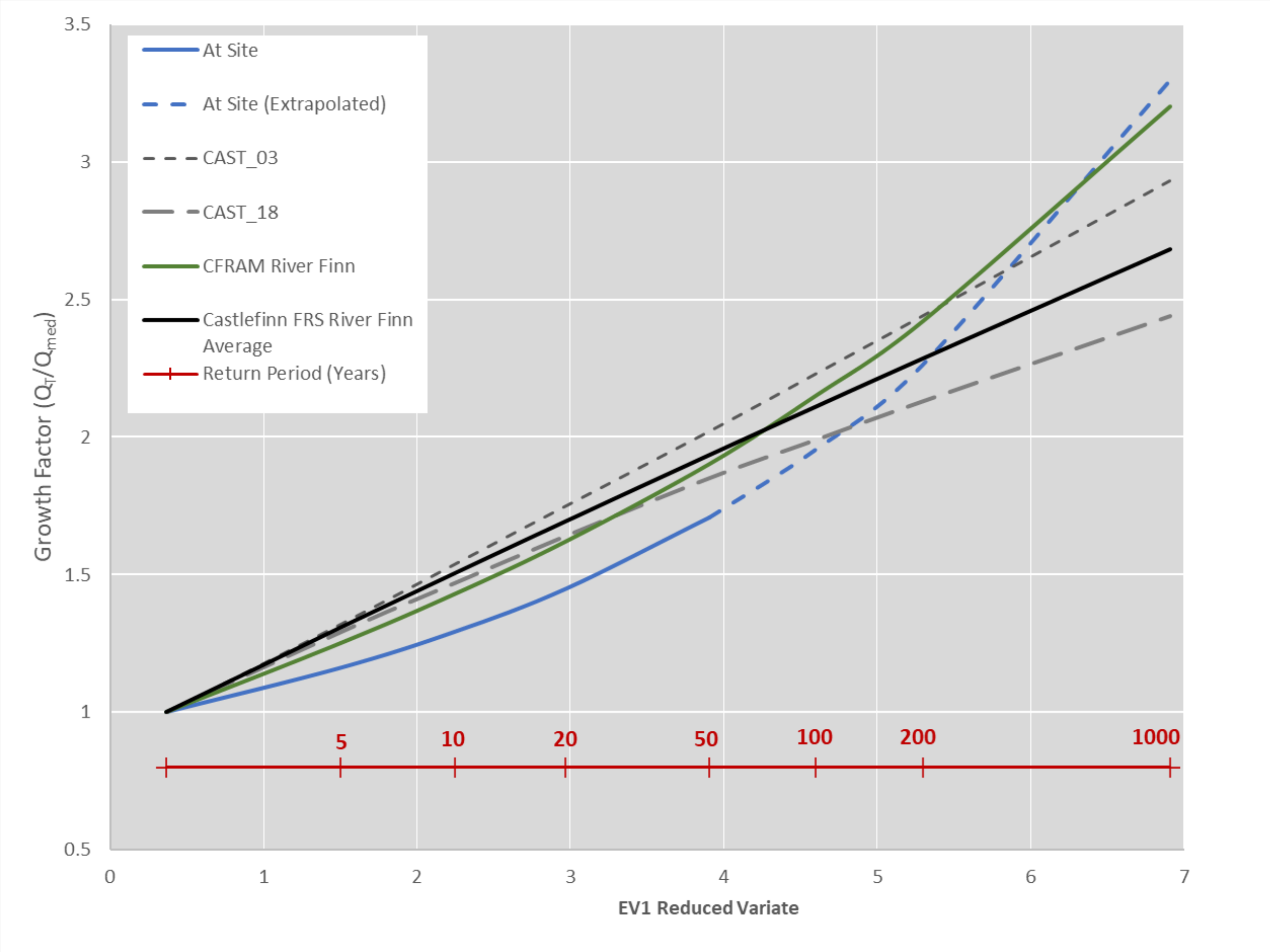


**Figure 3.3 River Finn Growth Curves v At-Site (Ballybofey) v CFRAM Study**

Growth factors for the tributaries were also generalised by taking the average growth curves from the four tributary growth curves (CAST_05, CAST_09, CAST_12 and CAST_14). The individual and average growth curves are shown in comparison to the CFRAM Study growth curve used for the Castlefinn tributaries Figure 3.4.

It can be seen from Figure 3.4 that there is a fair spread in the individual growth curves for the tributaries. Given the hydrological similarity and closeness of the tributaries, the spread is considered unrealistic and probably the result of differences in the pooling groups. The CFRAM Study growth curve is flatter and is derived from AMAX data that is outdated.

Again, the Castlefinn FRS average growth curve is taken forward as the basis of design flow estimation as it is derived from the most up-to-date and relevant pooled gauge data.

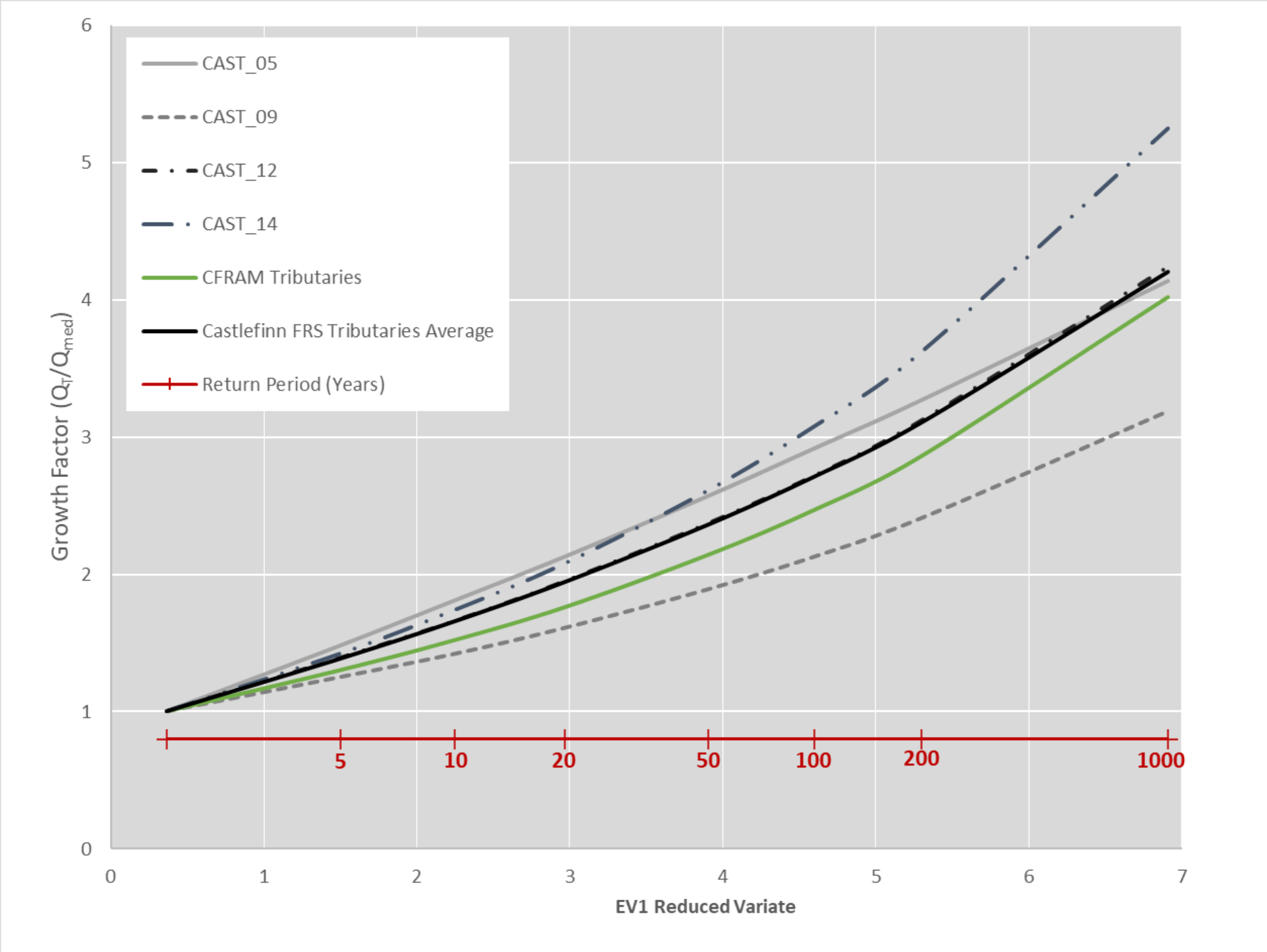


**Figure 3.4 Tributary Growth Curves v CFRAM Study**

## 3.3.5 Castlefinn FRS Final Design Flows

The final $Q_{med}$ values were combined with the generalised growth curves for the River Finn and the tributaries to result in the final peak design flows as set out in Table 3.11.

**Table 3.11 Final Peak Design Flows for Castlefinn FRS**

| HEP | 50% AEP | 20% AEP | 10% AEP | 5% AEP | 2% AEP | 1% AEP | 0.5% AEP | 0.1% AEP |
|---|---|---|---|---|---|---|---|---|
| **CAST_01** | 257.90 | 336.98 | 388.30 | 436.81 | 498.64 | 544.31 | 589.28 | 691.67 |
| **CAST_02** | 257.46 | 336.40 | 387.64 | 436.06 | 497.79 | 543.37 | 588.28 | 690.48 |
| **CAST_03** | 258.55 | 337.83 | 389.28 | 437.91 | 499.89 | 545.67 | 590.76 | 693.40 |
| **CAST_04** | 0.27 | 0.37 | 0.44 | 0.52 | 0.63 | 0.73 | 0.83 | 1.13 |
| **CAST_05** | 0.42 | 0.59 | 0.70 | 0.82 | 1.00 | 1.15 | 1.32 | 1.78 |
| **CAST_06** | 256.00 | 334.50 | 385.44 | 433.59 | 494.97 | 540.30 | 584.94 | 686.57 |
| **CAST_07** | 4.22 | 5.84 | 6.99 | 8.20 | 9.95 | 11.44 | 13.09 | 17.73 |
| **CAST_08** | 0.11 | 0.16 | 0.19 | 0.22 | 0.26 | 0.30 | 0.35 | 0.47 |

| HEP | 50% AEP | 20% AEP | 10% AEP | 5% AEP | 2% AEP | 1% AEP | 0.5% AEP | 0.1% AEP |
|---|---|---|---|---|---|---|---|---|
| **CAST_09** | 4.33 | 5.99 | 7.17 | 8.41 | 10.21 | 11.73 | 13.43 | 18.18 |
| **CAST_10** | 260.31 | 340.13 | 391.93 | 440.89 | 503.30 | 549.39 | 594.79 | 698.13 |
| **CAST_11** | 0.55 | 0.76 | 0.91 | 1.06 | 1.29 | 1.48 | 1.70 | 2.30 |
| **CAST_12** | 0.90 | 1.25 | 1.49 | 1.75 | 2.13 | 2.44 | 2.80 | 3.79 |
| **CAST_13** | 0.44 | 0.61 | 0.73 | 0.86 | 1.05 | 1.20 | 1.37 | 1.86 |
| **CAST_14** | 0.49 | 0.68 | 0.82 | 0.96 | 1.16 | 1.34 | 1.53 | 2.07 |
| **CAST_15** | 259.35 | 338.87 | 390.48 | 439.26 | 501.44 | 547.36 | 592.59 | 695.55 |
| **CAST_16** | 5.28 | 7.31 | 8.75 | 10.26 | 12.46 | 14.32 | 16.39 | 22.19 |
| **CAST_17** | 254.40 | 332.40 | 383.03 | 430.88 | 491.87 | 536.92 | 581.28 | 682.28 |
| **CAST_18** | 267.87 | 350.01 | 403.32 | 453.71 | 517.92 | 565.36 | 612.07 | 718.42 |

*Note: Grey Cells denote River Finn HEPs*

It can be seen from Table 3.11 that there are some small decreases in the design flows moving downstream along the River Finn which could appear counter-intuitive. This is occurring because of the effect of decreasing catchment descriptors moving downstream, such as SAAR (rainfall) and S1085 (main channel slope). This is outweighing the effect of increasing the catchment area within the FSU 7 variable $Q_{med}$ equation. Despite the catchment area getting larger, the effect of it getting flatter and drier moving downstream is leading to reducing $Q_{med}$ values at some locations. Whether this is realistic is uncertain, but it is known that there is significant floodplain attenuation in the lower Finn valley which could cause this effect. Ultimately the model will simulate if this effect is realistic and the simulated flows, taking account of the hydraulic performance of the Finn floodplain will represent the best estimates of flood flows in the lower Finn valley.

### 3.3.5.1 Comparison with the NW-NB CFRAM Study

It can be seen from Table 3.12 that the flows on the River Finn have reduced slightly (2-7%) from the CFRAM Study. This is primarily a result of a different approach to the issue of $Q_{med}$ estimates from the FSU ungauged (7 variable) catchment descriptor-based equation which results in a decreasing $Q_{med}$ moving down through the Finn Valley. In the CFRAM Study values of $Q_{med}$ were prevented from decreasing as it was considered unrealistic. For this project, given a better understanding of how the modelled flows perform moving down through the Finn Valley, and in particular the significant effect of floodplain attenuation, it was decided this could be realistic. Ultimately this has little bearing on the flood flows entered into the model and the best representation of the $Q_{med}$ flows at check point HEPs, such as CAST_03 and CAST_18 will be determined by the model. The difference is slightly larger at the 1% AEP design flows due to the slightly larger 1% AEP growth factor adopted in the CFRAM Study (see 3.3.4).

It can also be seen that the flows on the tributary watercourses at CAST_09 and CAST_16 have increased significantly from the CFRAM Study (13 – 36%). This is primarily due to the change to the FSU 5 variable equation for the estimation of $Q_{med}$. The larger increase in the 1% AEP flow is a result of the larger 1% AEP growth factor (Figure 3.4) adopted for this project.

The tributary represented by CAST_12, the Castlefinn watercourse, has seen the estimates of peak flow decrease. This was a result of a review of the catchment and site walkover which found the OSi river network shapefile to be incorrect and the catchment to be substantially smaller as a result (see Section 3.1).

**Table 3.12 Comparison of Castlefinn FRS Design Flows with NW-NB CFRAM Study (comparable HEPs)**

| CFRAM Study HEP | Area | Qmed ($m^3/s$) | 1% AEP ($m^3/s$) | Castlefinn FRS HEP | Area | Qmed ($m^3/s$) | 1% AEP ($m^3/s$) | % Change Qmed | % Change 1% AEP |
|---|---|---|---|---|---|---|---|---|---|
| **01043_RARPS (Ballybofey GS)** | 314.1 | 257.9 | 553.7 | **CAST_01** | 314.0 | 257.9 | 544.3 | 0% | -2% |
| **01_885_2_ RARPS** | 436.8 | 273.9 | 588 | **CAST_03** | 433.3 | 258.6 | 545.7 | -6% | -7% |
| **01_1887_2_RA** | 8.5 | 3.8 | 9.4 | **CAST_09** | 7.8 | 4.3 | 11.7 | 13% | 25% |
| **01_633_6_RA** | 3.9 | 1.1 | 2.7 | **CAST_12** | 2.4 | 0.9 | 2.4 | -18% | -11% |
| **01_654_4_RA** | 12.4 | 4 | 10.6 | **CAST_16** | 12.3 | 5.3 | 14.3 | 32% | 36% |
| **01_724b_1_RA** | 493.8 | 273.9 | 588 | **CAST_18** | 502.3 | 267.9 | 565.4 | -2% | -4% |

## 3.4 Design Hydrograph Estimation

### 3.4.1 Hydrograph Width Analysis

The previous sections discuss the process of arriving at design peak flows using statistical procedures from the FSU and FEH. These statistical methods of flood flow estimation don't however produce outputs of the catchment response. Catchment response is best represented using a hydrograph. This shows how the flow changes over time during an event and is analogous to a signature of a given catchment. Peak flow estimations and associated hydrographs are required for a hydraulic model to simulate design events and determine the impact of flood peaks and volumes over time.

The main characteristics of a hydrograph include the rising limb, time-to-peak and recession limb. A less responsive catchment will typically have a wide hydrograph, compared to a flashy catchment which will have a very steep and peaked shape. The area under a hydrograph is the total volume which can be used to inform storage capacities during optioneering flood defence measures.

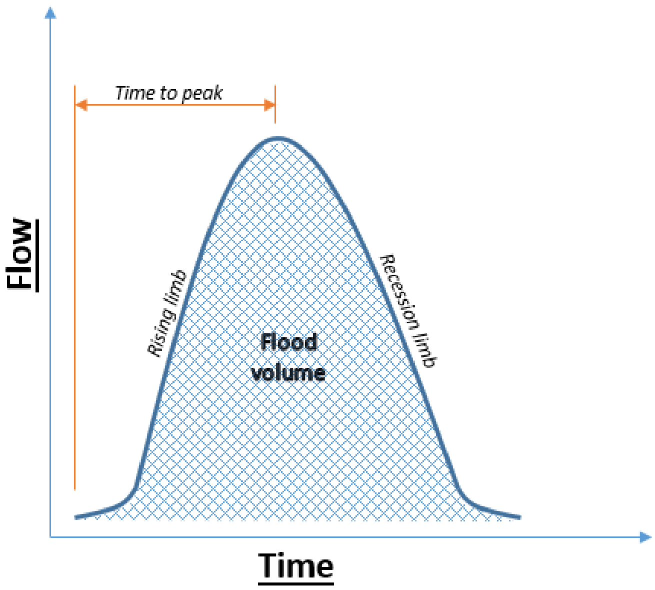


**Figure 3.5 The flood hydrograph**

A catchments response to rainfall (and subsequently the shape of its hydrograph) is affected by PCDs such as catchment area, drainage path slope and drainage path length. The approach to estimating flood hydrographs in the FSU is similar in principle to the estimation of $Q_{med}$ since it uses influential PCDs to arrive at an initial estimate of the hydrograph shape. The shape is then adjusted based on data from pivotal sites to achieve a hydrograph shape which is partially derived from observed data and to reduce uncertainties.

Hydrograph shapes for the CFRAM Study used the FSU hydrograph shape generator tool but they were effectively using estimation methods which were not grounded in data from the River Finn as no Finn stations were deemed appropriate for inclusion in the FSU library of hydrograph pivotal sites.

For this project, the hydrograph data for the Ballybofey gauging station was analysed and used as the basis for the design hydrograph shapes along the River Finn. The approach used leans heavily on the method developed by Archer *et al.* (2000) which is based on principles of Hydrograph Width Analysis (HWA). HWA aims to define the shape of the design flood hydrograph based on observed flood hydrographs. The premise is that hydrographs of floods occurring at a station are broadly similar in character and that the typical shape (or width across the range of percentiles of peak flow) of the hydrograph of a future flood - embodied in the design flood hydrograph – can be expected to reflect the general features of those which have already occurred.

The method considers all observed hydrographs represented within the AMAX series for the gauged catchment. Firstly, hydrographs are analysed to isolate the individual event shape with data from before and after this point removed. Hydrograph width is then determined for each decile of the peak flow by taking the median width. These median widths are combined to arrive at an averaged hydrograph shape using three key shape parameters:

- n - Shape parameter of Gamma distribution (and of UPO-ERR-Gamma model)
- Tr - Rise time (=translation parameter) of UPO-ERR-Gamma model)
- C - Recession parameter of UPO-ERR-Gamma model (hours)

HWA was applied to Ballybofey and also the Clady Alert (water level only) station record as part of the Lifford FRS with the reporting of that analysis replicated here. The normalised shapes of derived hydrographs can be scaled using the statistical design flows estimates once finalised (Table 3.11).

## 3.4.2 Hydrograph Width Analysis at Gauged Locations

The HWA was undertaken at the Ballybofey gauging station as the basis for the design inflow hydrographs on the River Finn. It was also undertaken on the DfI Clady Alert water level only gauge as an attempt to validate the design hydrograph shape along the lower reaches of the model. Initially, the FSU hydrograph shape generator was used at all ungauged locations to derive statistically informed catchment response parameters. HWA was used to anchor the FSU analysis to the observed hydrograph data within the Study Area.

To validate the HWA output hydrographs at gauged locations, RPS undertook a process of event extraction, normalisation, and superimposition. This process involved the following steps:

1. Locate all AMAX events in the continuous records,
2. Extract the events by taking a window of 24hrs preceding and succeeding the event peak flow,
3. Overlay events with their mean and median traces to generalise complexities in observed hydrographs affected by compounded rainfall events and antecedent conditions.
4. Superimpose the design outputs from the HWA exercise.

### 3.4.2.1 HWA validation for Finn at Ballybofey

The entire record period for the Ballybofey gauge was used in this validation process. It was concluded that the period before 1991 is extremely uncertain with noticeably disparate flows and key flood flow statistics. However, since the flows are derived from water levels, then it is appropriate to avail of the entire record and compares the outputs of the HWA, focussing only on the shape in terms of the key hydrograph characteristics. A total of 48 AMAX events were subsequently extracted from the continuous flow record.

Figure 3.6 presents the continuous flow data recorded at Ballybofey and the selected peak AMAX events used in this design hydrograph validation process.

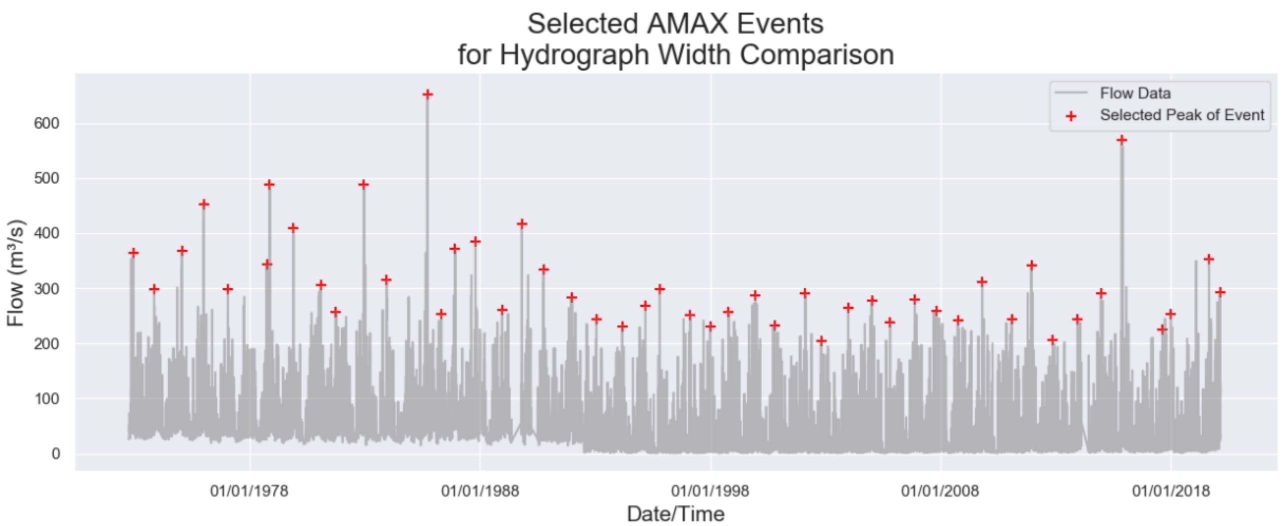


**Figure 3.6 Ballybofey selected AMAX events for hydrograph shape validation**

The AMAX events were extracted and normalised before superimposing the outputs of the HWA exercise as well as generating mean and median observed hydrographs to aid the comparison (Figure 3.7).

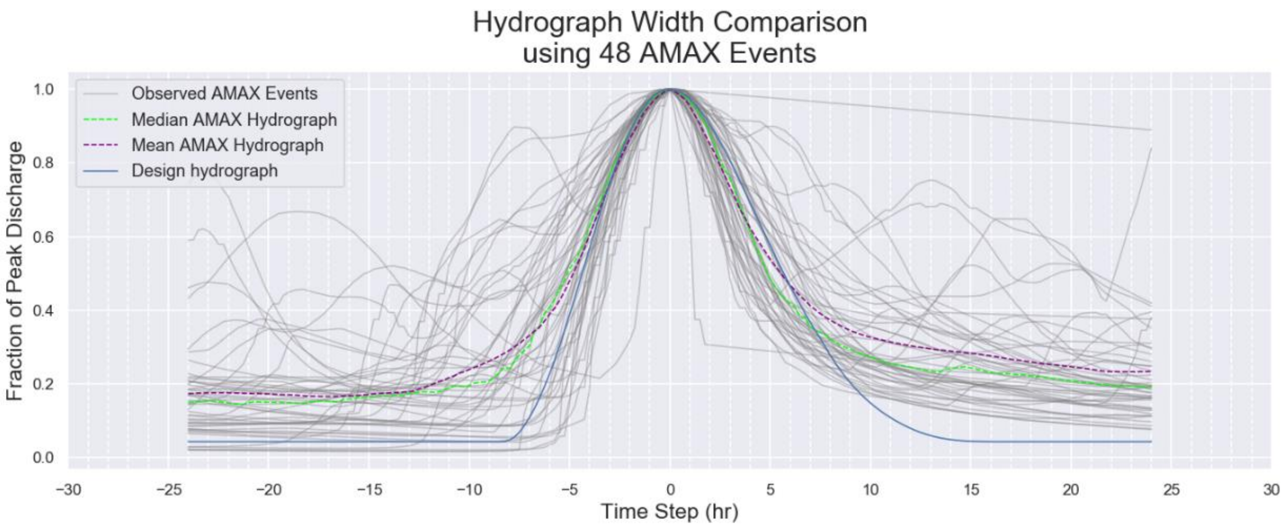


**Figure 3.7 Ballybofey hydrograph shape validation**

### 3.4.2.2 HWA validation for CAST_17

The Clady at Clady Alert is a water level-only gauge located on the lower reaches of the Finn. There is limited data available to undertake hydrograph width validation. A series of AMAX events based on the water level at the Clady Alert gauging station results in only three AMAX events for comparison with the output from the FSU shape generator. Additional events were selected by taking the maximum weekly water level and querying out fewer extreme events using a threshold of four metres. This resulted in 13 events to compare the design hydrograph width at CAST_17. The extracted events include the notable flood which occurred in August 2017. The selected events extracted from the continuous time series of water level data at the Clady Alert gauge are presented in Figure 3.8.

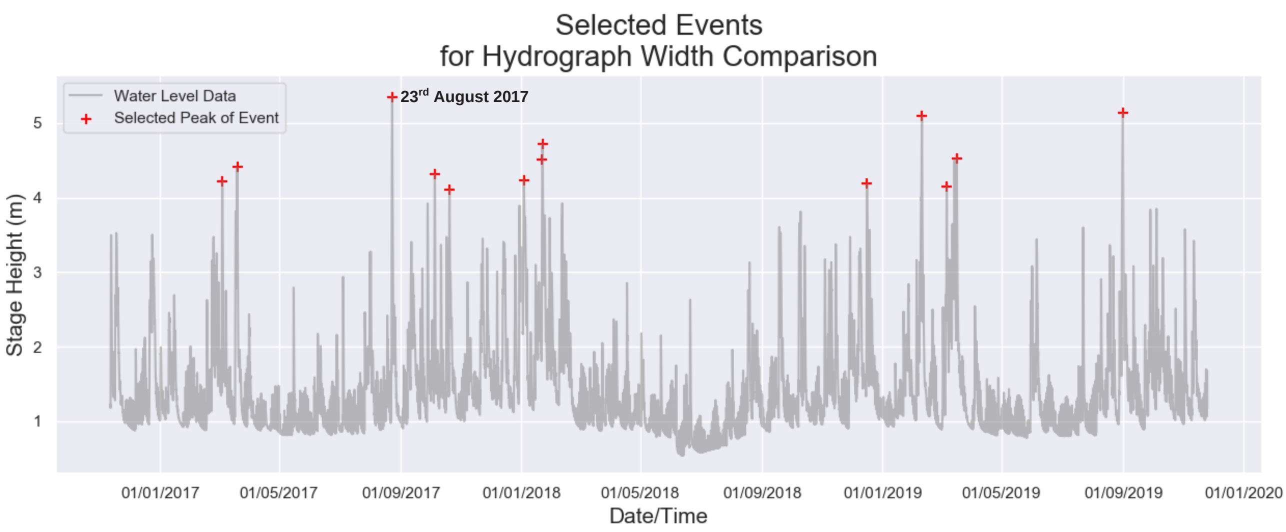


**Figure 3.8 Clady Alert selected events for hydrograph shape comparison**

The events were extracted and normalised before superimposing the outputs of the FSU shape generator exercise as well as generating mean and median observed hydrographs to aid the comparison (Figure 3.9).

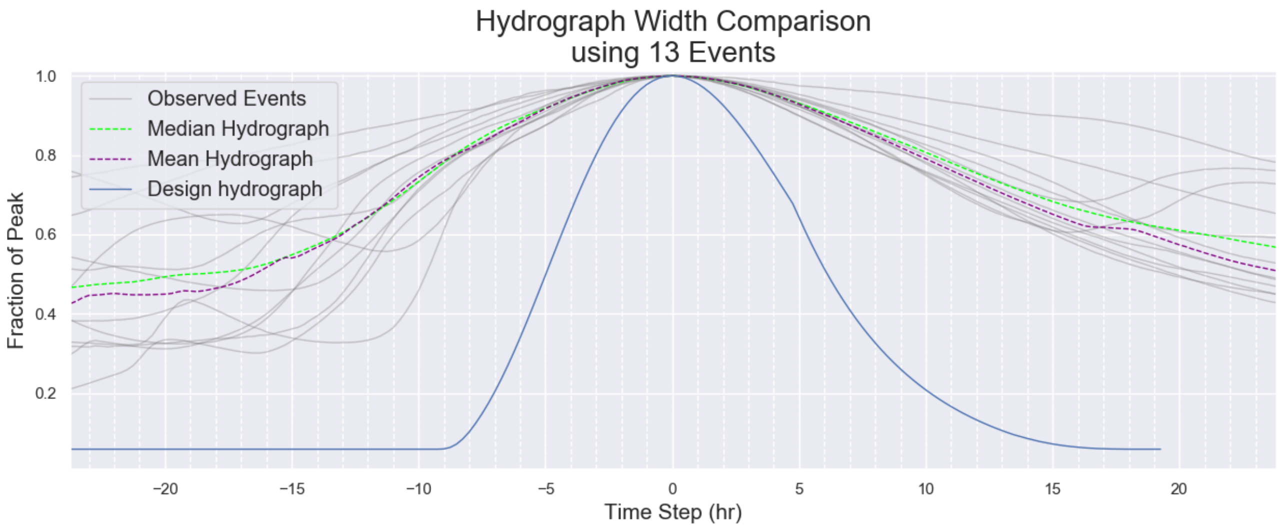


**Figure 3.9 Clady Alert hydrograph shape validation**

Considering the key hydrograph shape characteristics, this design hydrograph is not appropriate for representing the catchment response at CAST_17. This finding could also suggest concern for the hydrograph shape further downstream at the ungauged location of CAST_18. The observed data may be capturing the floodplain attenuation in the lower reaches of the Finn Valley and the backwater effect from the confluence at Lifford. Subsequently, the median hydrograph shape (based on HWA) was considered a more realistic design hydrograph shape, and the FSU shape generator used to forge a new set of shape parameters to better represent the catchment response at CAST_17. The output of the revised design hydrograph shape following calibration with the Clady Alert observed hydrograph shape is shown in Figure 3.10.

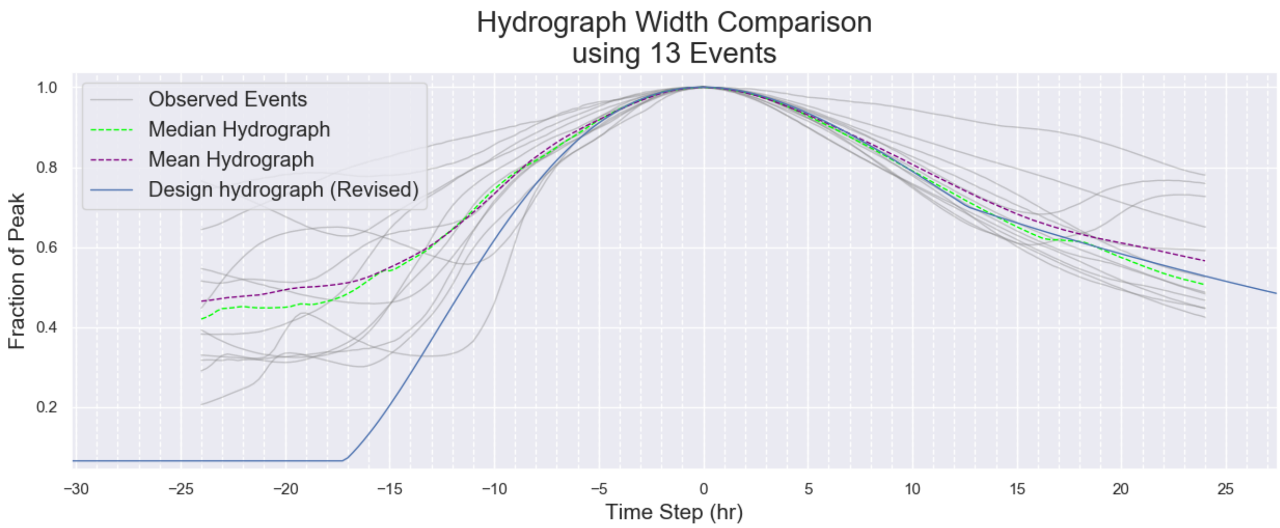


**Figure 3.10 Clady Alert hydrograph shape validation - revised**

The revised shape better reflects the response of the Finn on the lower reaches based on the Clady Alert gauging station events. It would also be prudent to adopt the same design hydrograph for CAST_18 since the true catchment response downstream near the Finn / Foyle confluence is likely to be similar. The overall shape and timings for the design hydrograph are a good representation and adequate for taking forward for hydraulic modelling at this location in the study area.

### 3.4.3 Design Hydrograph Shapes

#### 3.4.3.1 Ungauged Tributaries

The FSU shape generator produced hydrographs for the ungauged HEPs. The most hydrologically similar pivotal site gauging station was initially chosen for the tributary hydrographs. Following an initial review of the hydrograph shapes, RPS was concerned the hydrograph width was too large leading to unrealistic flood volumes for option development.

The FSU shape generator initially suggested the use of the White Bridge gauging station (22009) located in a small catchment near Killarney, Co. Kerry. This catchment is remote from the Study Area and is partially urbanised.

Following the HWA of the Gortinlieve gauging station record (01016) this small catchment is available within the list of hydrograph pivotal sites. The Gortinlieve gauging station (01016) was used as the basis for hydrograph shape parameter adjustment on all of the small catchments affecting Castlefinn. The catchment does not represent the most hydrologically similar pivotal site for hydrograph shape, but it is a small catchment which is reasonably hydrologically similar and geographically close, being located further north within the Foyle catchment. Hence the resulting hydrograph volume could be considered uncertain given the subjective nature of the choice of hydrograph pivotal site. In light of this RPS applied the UK-based Revitalised Flood Hydrograph (ReFH) 2 model to one of the critical tributary catchments at Castlefinn, the Castlefinn watercourse. This alternative method utilises the Flood Estimation Handbook (FEH) catchment descriptors which are available at Castlefinn. Rainfall from the FEH DDF 2013 model is applied within a rainfall-runoff method based on the Unit Hydrograph method. The ReFH2 method is considered useful for hydrograph estimation as there is a direct relationship between design rainfall and hydrograph volume, i.e., the water balance is accounted for. This is not the case for the FSU statistical-based methods for hydrograph generation. The effect of the choice of hydrograph pivotal site for the Castlefinn watercourse catchment at CAST_11, and also the ReFH2 rainfall-runoff method hydrograph is shown for comparison purposes in Figure 3.11.

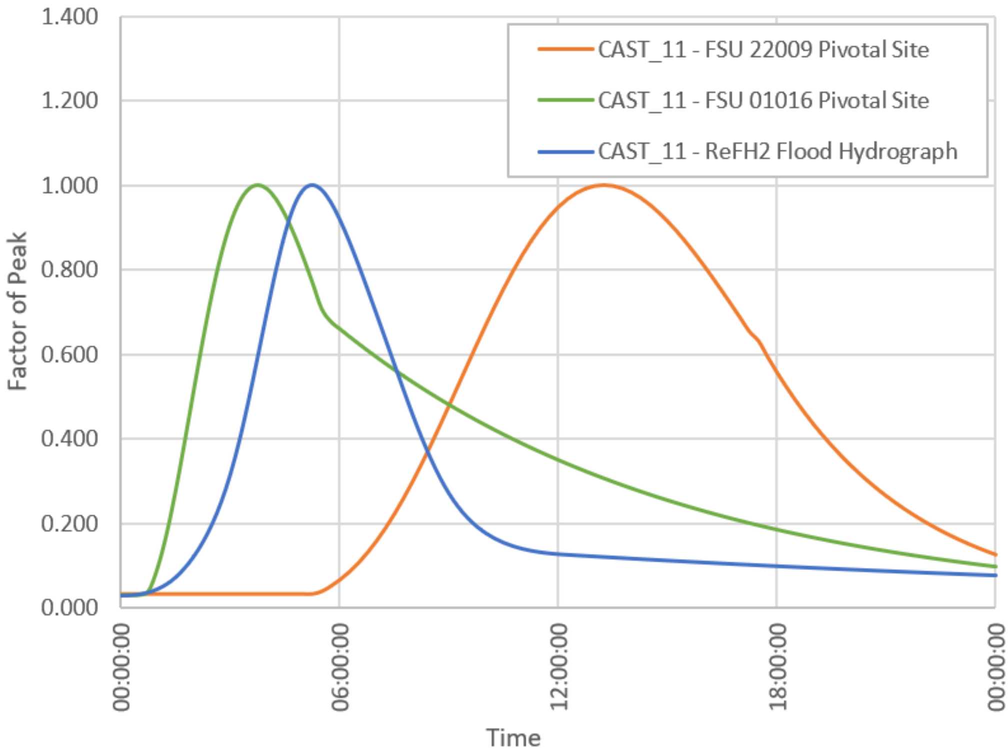


**Figure 3.11 Hydrograph Shape at CAST_11 based on different FSU Pivotal site and ReFH2 method**

It can be seen from Figure 3.11 that there is wide variation in the hydrograph shape derived from the FSU method depending on which pivotal site is chosen. The ReFH2 method, used here for validation, suggests that the Gortinlieve station (01016) does result in a more realistic hydrograph width, albeit the FSU design hydrograph based on Gortinlieve does still represent a conservative estimate of volume given the long recession limb.

#### 3.4.3.2 River Finn

As discussed in 3.4.2.2, the initial estimated FSU hydrograph at CAST_17 on the River Finn was found to be unrepresentative of the catchment response at the Clady Alert gauge which led to a revision of the shape parameters and the adoption of the same hydrograph for CAST_18. Furthermore, the shape parameters of the intermediate hydrographs CAST_10 and CAST_15 along the River Finn were manually edited to provide a smooth transition between the observed, fast responding hydrograph at Ballybofey (CAST_01) and the more attenuated hydrograph at the Clady Alert gauge (CAST_17).

In addition to hydrograph width analysis, an assessment was undertaken to ensure hydrograph timings are truly representative of the observed catchment response between HEPs on the River Finn. Events were selected from the continuous flow and water level records before being normalised and the peak timings calculated. Event timings vary, likely due to the various rainfall profiles with complex temporal and spatial distributions, as well as differing antecedent conditions leading up to the event and the magnitude of the event (since larger events tend to see flood waters with higher velocities).

Due to the limited data available at the Clady Alert gauge on the River Finn, a subset of events was selected. In total, 160 largest events on the River Finn within the concurrent record period of the Ballybofey flow gauge and the Clady Alert water level gauge were extracted and the time between peaks was calculated. The events include the second largest event on record at the Ballybofey gauge station which occurred in August 2019. A subset of the 12 largest events within the concurrent record is presented in Figure 3.12.

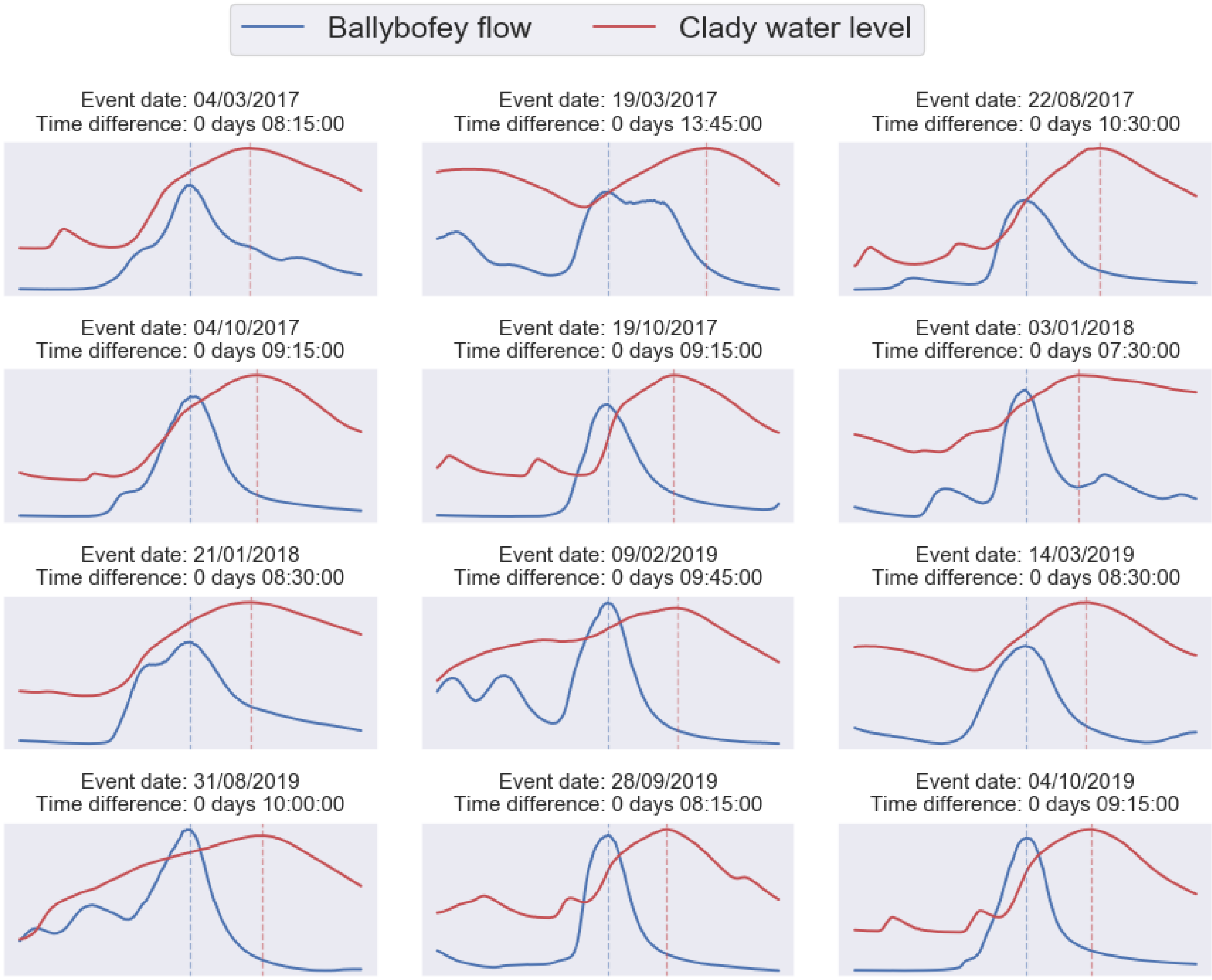


**Figure 3.12 River Finn event timings**

The resulting average time between peaks over all 160 events is approximately seven hours. The above subset of timings appears longer than seven hours on average, but larger events tend to see flood waters with higher velocities, thus reducing the time between peaks between the gauge at Ballybofey and the Clady gauge.

The findings from this analysis were used to ensure the time between peaks on the River Finn between Ballybofey and Clady is reflected in the design hydrographs and inflows for hydraulic modelling.

## 3.4.4 Final Design Hydrograph Shape Parameters

The initial hydrograph shape parameters, the hydrograph pivotal site and any comments on the shape parameters generated from the FSU approach are provided in Table 3.13.

**Table 3.13 FSU Hydrograph Shape Parameters**

| HEP | n | Tr | C | Hydrograph Pivotal Site / Comments |
|---|---|---|---|---|
| CAST_01 | 10.00 | 12.70 | 3.17 | 01043 |
| CAST_02 | 9.65 | 13.30 | 3.75 | Average of CAST_02 & CAST_03 |
| CAST_03 | 9.29 | 13.89 | 4.32 | 01043 |
| CAST_04 | 5.27 | 4.13 | 9.48 | 01016 |

| HEP | n | Tr | C | Hydrograph Pivotal Site / Comments |
|---|---|---|---|---|
| CAST_05 | | | | |
| CAST_06 | 9.27 | 14.04 | 4.37 | 01043 |
| CAST_07 | 8.55 | 2.55 | 1.68 | 01016 |
| CAST_08 | | | | |
| CAST_09 | | | | |
| CAST_10 | 7.00 | 14.86 | 10.00 | Manual edit to parameters to transition to Clady Alert |
| CAST_11 | 5.27 | 3.83 | 9.48 | 01016 |
| CAST_12 | | | | |
| CAST_13 | 5.97 | 4.21 | 6.07 | 01016 |
| CAST_14 | | | | |
| CAST_15 | 4.50 | 15.00 | 25.00 | Manual edit to parameters to match Clady Alert |
| CAST_16 | 10.42 | 12.21 | 3.96 | 01043<br>22009 |
| CAST_17 | 4.00 | 17.00 | 35.00 | Manual edit to parameters to match Clady Alert |
| CAST_18 | 3.50 | 17.25 | 40.00 | |

*Note: Grey Cells denote River Finn HEPs*

Some hydrograph rising limb start times have been altered such that they commence around the same time, to bring them in line with the majority of the model hydrographs. This is considered a more realistic scenario whereas the FSU shape generator can result in a long delay at the start of the hydrograph as it attempts to form the shape around the central peak. This delay is considered a quirk of the estimation method rather than any delay grounded in the catchment characteristics. Furthermore, hydrographs have been shifted to ensure that the timings are such that the flows at the check flow HEPs are met. This is checked before modelling by summing all the inflow hydrographs upstream of a check flow HEP to ensure there is sufficient flow to reach the downstream check flow. It is also checked following initial modelling to ensure that travel time within the model does not result in misalignment of hydrographs leading to check flows not being reached. A further minor reason for shifts in hydrograph time to peak is to fit them to regular timesteps of 15 minutes. i.e., estimated hydrograph peak timings (Tr) are moved to the nearest quarter hour timestep. The alterations which have been applied to the hydrograph timings are presented in Table 3.14.

**Table 3.14 Original and Final Hydrograph Peak Timings**

| HEP | Original Tr (Hours) | Final Tr (Hours) | Shift (Hours) |
|---|---|---|---|
| CAST_01 | 12.70 | 11.00 | -1.70 |
| CAST_02 | 13.30 | 11.75 | -1.55 |
| CAST_03 | 13.89 | 12.255 | -1.64 |
| CAST_04 | 4.13 | 5.75 | 1.62 |

| HEP | Original Tr (Hours) | Final Tr (Hours) | Shift (Hours) |
|---|---|---|---|
| CAST_05 | 4.13 | 5.75 | 1.62 |
| CAST_06 | 14.04 | 12.75 | -1.29 |
| CAST_07 | 2.55 | 5.00 | 2.45 |
| CAST_08 | 2.55 | 5.00 | 2.45 |
| CAST_09 | 2.55 | 5.00 | 2.45 |
| CAST_10 | 14.86 | 14.75 | -0.11 |
| CAST_11 | 3.83 | 7.00 | 3.17 |
| CAST_12 | 3.83 | 7.50 | 3.67 |
| CAST_13 | 4.21 | 5.25 | 1.04 |
| CAST_14 | 4.21 | 5.45 | 1.24 |
| CAST_15 | 15.00 | 15.00 | 0.00 |
| CAST_16 | 12.21 | 12.25 | 0.04 |
| CAST_17 | 17.00 | 17.50 | 0.00 |
| CAST_18 | 17.50 | 17.50 | 0.00 |

*Note: Grey Cells denote River Finn HEPs*

The output semi-dimensional hydrographs taken forward for input into the hydraulic model are presented in Figure 3.13.

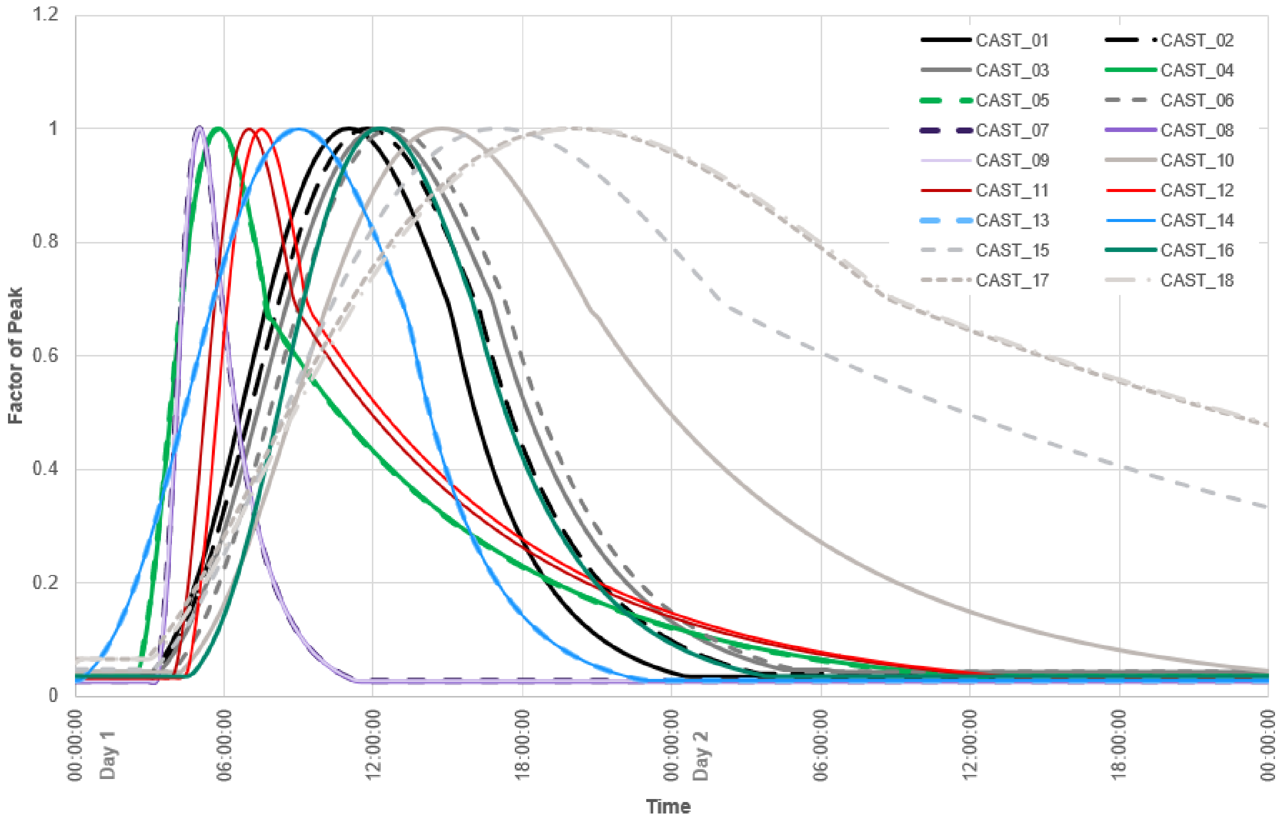


**Figure 3.13 Final Design Hydrograph Shapes**

### 3.4.5 Lateral inflow generation

Following the development of design peak flows and hydrographs for modelling at the various HEPs, it is necessary to develop the complete set of inflows for the hydraulic model. The design hydrographs for HEPs which lie at the upstream extents of the model, CAST_01, 04, 07, 08, 11, 13 and 16 can be directly entered into the hydraulic model. However, to reach the flows at intermediate and downstream HEPs the inflow from the lateral catchment between HEPs must be estimated. A typical approach to generating these lateral inflows is to deduct the hydrograph for the upstream HEP from the downstream or intermediate HEP. This method can prove problematic, particularly in the case of catchments where there is significant attenuation in the area where the lateral catchment is to be applied. The modelled River Finn reaches are a good example of this with the peak flow between CAST_01 and CAST_06 estimated to decrease slightly (-1%) despite a large increase in the catchment area (+40%).

The preferred approach is to estimate the lateral inflow hydrograph by scaling the downstream HEP hydrograph to the lateral catchment area (between the subject HEP and the next HEP upstream).

$$Lateral\ Inflow = \frac{Lateral\ Catchment\ Area}{Downstream\ HEP\ Area} \times Downstream\ Check\ Flow$$

The result of this approach in the case of the combined lateral inflows between CAST_01 and CAST_06 is that a total peak flow of 166 $m^3$/s (31%) is added via a more realistic hydrograph profile as a lateral inflow to the model between the HEPs on the Finn.

As an initial check before modelling the sum of the inflow hydrographs is calculated at each of the intermediate and downstream HEPs to estimate the total inflow to the model at that point. This approach cannot account for the hydraulic effects on flows within the model such as flood peak travel time and attenuation but provides a useful check before modelling. In the case of the River Finn, the sum of inflows at CAST_18 is 742 $m^3$/s. This is 31% higher than the estimated peak flow at CAST_18 of 565 $m^3$/s. However, it is known following initial modelling that the model in the lower reaches of the Finn will act to significantly attenuate the peak flows and elongate the flood hydrograph.

A complete check of the anchoring of the modelled flows to the hydrological estimates is provided in the hydraulics report.

The complete model inflows are provided in tables in a spreadsheet format accompanying this report.

# 4 DOWNSTREAM BOUNDARY

## 4.1 Fluvial - Fluvial Joint Probability

Flooding along the lower reaches of the River Finn including at Castlefinn is greatly affected by the fluvial conditions downstream in the River Foyle. This is evidenced by the August 2017 event when there was significant flooding on the River Finn despite a less than $Q_{med}$ or 2-year return period event recorded upstream at Ballybofey (see Table 2.1). This event, as analysed through the Lifford FRS Hydrology Report[3] was found to have had an estimated return period on the Foyle of 35-50 years.

The Lifford FRS Hydrology Report provides an analysis of a synthetic gauge record at the confluence of the Rivers Finn and Mourne at the top of the River Foyle by combining the flow records from both catchments. The combining of the gauge records effectively produces an observed history of combined flows downstream of the confluence. The joint probability conditions are inherently captured within the EVA of these synthetic records which effectively supersedes any requirement for a complex joint probability analysis following the methods set out in FD2308 (the guidance for joint probability analysis provided by DEFRA). The Lifford model is therefore considered to represent accurately the joint probability flow conditions at the Mourne and Finn confluence (downstream boundary of the Castlefinn study area) by replicating flow conditions which are validated against the synthetic combined record downstream of the confluence.

The downstream design and calibration water level boundary conditions at the bottom of the River Finn are extracted from the Lifford FRS model. The Lifford FRS Hydrology Report found that the Finn is the critical catchment for flooding at Lifford despite not being the largest. This means that the design event frequency conditions at Lifford occur when the critical flow conditions are realised along the River Finn. As previously noted, flooding can be driven by the Mourne / Foyle also but the largest flood events at both Lifford and Castlefinn can be shown to have occurred when the Finn recorded its largest peak flows. As a result, the simulated design event water level profile for the lower River Finn from the Lifford FRS model is used for the design event downstream water level boundary for the Castlefinn hydraulic model. For example, the 1% Annual Exceedance Probability (AEP) water level for the lower River Finn from the Lifford FRS model was used as the downstream boundary condition for the 1% AEP Castlefinn FRS model.

The tributaries of the River Finn have been assumed to generate critical flood conditions during the critical event on the River Finn. In the absence of hydrometric data on any of these tributaries, this is considered an appropriate, conservative approach in light of the uncertainty associated with no data upon which to base a Joint Probability assessment. Much of the River Finn catchment is characterised by a fast response to rainfall events, with flood flows generated mainly in the flashy headwater catchments and tributaries running off the sides of the valley. Furthermore, past flood events indicate that these tributaries have been in flood during the same events as the River Finn (i.e., 2015 flood events) and the approach is somewhat validated by the simulation of calibration events where this approach was found to replicate the flood extents and depths in areas where flooding is determined by both the Finn and tributary catchments (e.g., at the CPI centre).

Moving down through the model the approach of specifying intermediate HEPs at key locations downstream of tributaries, checking the sum of the inflows and then checking the peak flows generated in the model ensures that the correct frequency conditions are being replicated in the model downstream of confluence points.

## 4.2 Downstream Boundary Timing

The timing of the Castlefinn inflows with the downstream water level boundary condition can be shown to be critical through the hydraulic model. To gauge the realistic timing of boundary conditions it is useful to consider the observed timings of peaks between the Ballybofey gauge, representing the CAST_01 inflow and the

[3] Lifford Flood Relief Scheme Hydrology Report, Doc no: IBE1674_Rp_02

Drumnabuoy House gauging station. The Drumnabuoy House gauging station is a good proxy for the Foyle flow conditions given the location of the gauge just upstream of Strabane, the fact it represents the main Foyle catchment inflows and its hydrological independence from the Ballybofey gauge. The flow hydrographs from four selected recent flood events are shown in Figure 4.1.

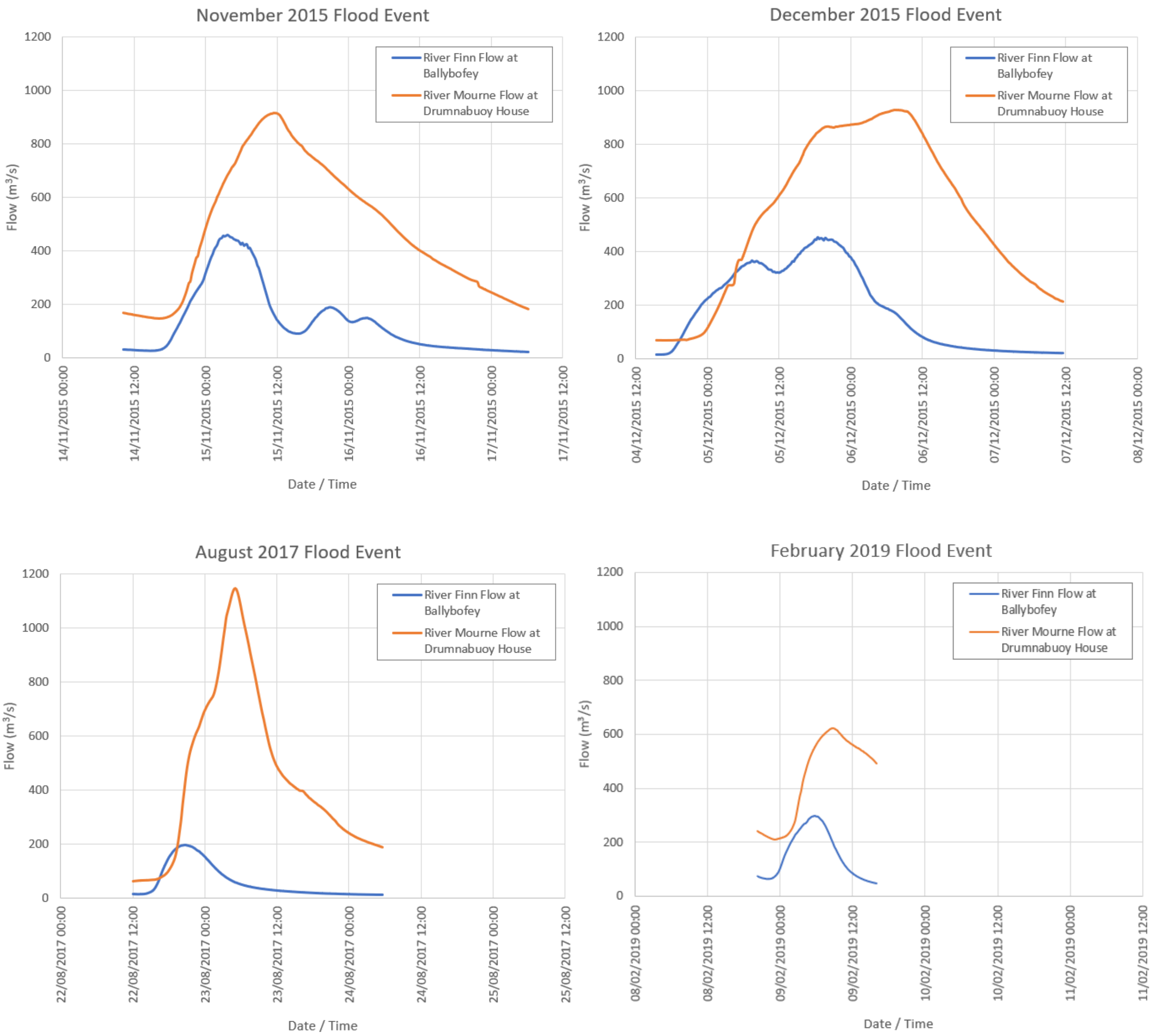


**Figure 4.1 Selected Observed Flood Hydrographs for Mourne and Finn**

It can be seen from Figure 4.1 that the flood peak timings between the two adjacent catchments are relatively close. The travel time of the hydrograph from the Drumnabuoy House gauging station, based on hydraulic modelling from the Lifford FRS to the confluence is estimated to be 0.5 hours. The travel time of the hydrograph from Ballybofey to the confluence is estimated to be seven hours (Section 3.4.3).

The average observed time between the flood event hydrograph peaks shown in Figure 4.1 is 8 hours 15 minutes. Given the travel time to the confluence of the flood peaks, this indicates that in past flood events both rivers have peaked at the same time with the Finn possibly peaking marginally earlier.

This has been replicated in the model with the timing of the downstream design boundary water levels extracted from the Lifford model timed to peak 8 hours after the main inflow hydrograph at CAST_01.

# 5 SENSITIVITY ANALYSIS

Hydrological analysis and design flow estimation are probabilistic assessments which originate from observed data. The long-term conditions which affect the observations, whether they are climatic or catchment-based, have been shown to varying degrees to be changing over time. The following factors which may affect the quality of both the analysed historic events and the estimation of the future design events are listed below:

- Hydrometric data record length and gaps
- Hydrometric data quality (classified in terms of the rating confidence)
- Standard error of flow estimation (catchment descriptor-based) techniques
- Future catchment changes, urbanisation, afforestation, sedimentation etc.
- Climate change

The above list is not exhaustive but seeks to identify the main potential sources of uncertainty in the hydrological analysis. It is not possible to make a quantitative assessment of all of the uncertainties as some of the factors are extremely complex. Nevertheless, it is important that an assessment is made such that the results can be taken forward and built upon in the hydraulic modelling phase. It is also important that the potential sources of uncertainty in the hydrological analysis and design flow estimation are flagged such that the integrated process of refining the hydrological inputs and achieving model calibration can be achieved more efficiently through a targeted approach. A qualitative assessment has therefore been undertaken to assess the potential for uncertainty/sensitivity.

The assessment used to derive a score for the uncertainty in the hydrological analysis is based on the approach adopted for the CFRAM Studies. The parameters affecting uncertainty are assessed out of a possible maximum score of 20 based on the frameworks set out in the CFRAM Study.

The CFRAM Study Guidance Note 22 derived a range of uncertainty factors associated with the FSU methodologies for deriving peak flows. The uncertainty associated with $Q_{med}$ for ungauged catchments is 1.37 under FSU but for well-gauged catchments with long records can be as low as 1.06. It is appropriate that these error ranges are applied as a sensitivity factor to the $Q_{med}$ flows for Castlefinn based on the scores derived through the assessment. The guidance note also suggests that for more extreme design flood events where the uncertainty is inherently higher a further factor should be applied based on the known uncertainties. The recommended uncertainty factors are adapted for Castlefinn into recommendations to be applied to the 10% and 1% AEP design events as shown in Table 5.1.

**Table 5.1 Uncertainty Factors to be applied to Castlefinn**

| Event AEP% | Summed Score | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 |
| 10% | 1.06 | | | | 1.14 | | | | | | 1.21 | | | | | 1.29 | | | | 1.37 |
| 1% | Use 10% uncertainty factor x 1.1 | | | | | | Use 10% uncertainty factor x 1.2 | | | | | | Use 10% uncertainty factor x 1.3 | | | | | | | Use 10% factor x 1.5 |

Uncertainty factors for Castlefinn have been derived based on the quality of the available hydrometric data, the uncertainty in the catchment data and the application of the final chosen design flow methodology to the subject catchment (i.e., higher uncertainty in small catchments or those with extreme catchment characteristics).

The scores for the various aspects of uncertainty for each HEP, the summed score, the uncertainty factors applied and the upper bound uncertainty flows to be modelled are shown in Table 5.2.

**Table 5.2 Summary of Uncertainty Scores**

| Reach | HEP | Observed Data (Out of 10) | Catchment Data (Out of 5) | Ungauged Flow Estimates (Out of 5) | Comments | Summed Score (Out of 20) | 10% AEP Uncertainty Factor | 10% AEP Uncertainty Flow | 1% AEP Uncertainty Factor | 1% AEP Uncertainty Flow |
|---|---|---|---|---|---|---|---|---|---|---|
| River Finn | CAST_01 | 2 | 1 | 1 | High certainty at gauging station following rating review. Applicability of gauge data drops moving downstream. Catchment well defined under FSU. | 4 | 1.06 | 411.60 | 1.17 | 634.66 |
| | CAST_02 | 4 | 1 | 1 | | 6 | 1.14 | 441.90 | 1.37 | 743.34 |
| | CAST_03 | 4 | 1 | 1 | | 6 | 1.14 | 443.77 | 1.37 | 746.48 |
| N.W. Tributary (Bridge Burn Stream) | CAST_04 | 8 | 3 | 3 | Ungauged and high uncertainty in the pivotal site. Moderate uncertainty in catchment data and FSU methods at a small catchment scale. | 14 | 1.21 | 0.54 | 1.57 | 1.14 |
| | CAST_05 | 8 | 3 | 3 | | 14 | 1.21 | 0.85 | 1.57 | 1.81 |
| River Finn | CAST_06 | 4 | 1 | 1 | Applicability of gauge data drops moving downstream. Catchment well defined under FSU. | 6 | 1.14 | 439.40 | 1.37 | 739.13 |
| S.W. Tributary (Tieveback) | CAST_07 | 8 | 3 | 3 | Ungauged and high uncertainty in the pivotal site. Moderate uncertainty in catchment data and FSU methods at a small catchment scale. | 14 | 1.21 | 8.46 | 1.57 | 18.00 |
| | CAST_08 | 8 | 3 | 3 | | 14 | 1.21 | 0.22 | 1.57 | 0.48 |
| | CAST_09 | 8 | 3 | 3 | | 14 | 1.21 | 8.67 | 1.57 | 18.46 |
| River Finn | CAST_10 | 4 | 1 | 1 | Applicability of gauge data drops moving downstream. Catchment well defined under FSU | 6 | 1.14 | 446.80 | 1.37 | 751.57 |
| N.E. Tributary (Castlefinn) | CAST_11 | 8 | 3 | 3 | Ungauged and high uncertainty in the pivotal site. Moderate uncertainty in catchment data and FSU methods at a small catchment scale. | 14 | 1.21 | 1.10 | 1.57 | 2.33 |
| | CAST_12 | 8 | 3 | 3 | | 14 | 1.21 | 1.81 | 1.57 | 3.84 |
| S.E. Tributary (Corcullion) | CAST_13 | 8 | 3 | 3 | | 14 | 1.21 | 0.89 | 1.57 | 1.89 |
| | CAST_14 | 8 | 3 | 3 | | 14 | 1.21 | 0.99 | 1.57 | 2.10 |
| River Finn | CAST_15 | 4 | 1 | 1 | Applicability of gauge data drops moving downstream. Catchment well defined under FSU | 6 | 1.14 | 445.15 | 1.37 | 748.79 |
| Dresnagh Tributary | CAST_16 | 8 | 3 | 3 | Ungauged and high uncertainty in the pivotal site. Moderate uncertainty in catchment data and FSU methods at a small catchment scale. | 14 | 1.21 | 10.59 | 1.57 | 22.52 |
| River Finn | CAST_17 | 4 | 3 | 2 | Applicability of gauge data drops moving downstream. Some uncertainty in FSU catchment data in the lower reaches | 9 | 1.14 | 436.65 | 1.37 | 734.50 |
| | CAST_18 | 4 | 3 | 2 | | 9 | 1.14 | 459.78 | 1.37 | 773.41 |

# 6 DESIGN RAINFALL

Section 1.4 indicates that there is some risk of pluvial flooding, particularly in the area at the junction of the N15 / R235 in front of McGlynn's restaurant. The risk of pluvial flooding appears to be related to fluvial conditions, given the pluvial flooding locations reported are along the route of small watercourses and reported alongside fluvial flooding.

Design pluvial (rainfall) inputs are necessary as the basis of the assessment of pluvial flood risk. Design rainfall inputs are derived for use as boundary conditions within rainfall-driven hydraulic models/calculations where necessary to simulate and map the flood risk from direct rainfall. Rainfall sums for a range of durations are extracted from the Depth Duration Frequency (DDF) model for the relevant sub-catchment or point that best represents the drainage sub-catchment in question.

RPS are aware of a 15-minute rain gauge located at Raphoe, approximately 9km to the north of Castlefinn. It is operated by the OPW. This rain gauge may be used to provide high-resolution rainfall data for rainfall calibration events during the project lifespan however, it has not been used at this stage of the analysis as the record does not cover any of the pluvial flood events which have been observed.

## 6.1 Design Rainfall Sums

Design rainfall sums have been extracted from the FSU DDF model[4] for the suite of return periods. Rainfall sums have been extracted as point data from the FSU 2km grid point closest to the Castlefinn study area. FSU design rainfall sums (mm) are presented in Table 6.1.

**Table 6.1 FSU Rainfall Sums (mm), Castlefinn**

| Event Duration Hours | AEP (%) / Return Period (Year) | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | 50% (2) | 20% (5) | 10% (10) | 5% (20) | 2% (50) | 1% (100) | 0.5% (200) | 0.1%* (1000) |
| **0.25** | 6.9 | 9.6 | 11.7 | 14.1 | 17.7 | 21 | 24.9 | 36.9 |
| **0.5** | 8.9 | 12.2 | 14.7 | 17.5 | 21.8 | 25.6 | 30.1 | 43.9 |
| **1** | 11.4 | 15.5 | 18.5 | 21.8 | 26.8 | 31.2 | 36.4 | 52.4 |
| **2** | 14.7 | 19.6 | 23.2 | 27.1 | 32.9 | 38.1 | 44 | 62.2 |
| **3** | 17.1 | 22.5 | 26.5 | 30.8 | 37.2 | 42.8 | 49.2 | 68.6 |
| **4** | 19 | 24.9 | 29.1 | 33.7 | 40.5 | 46.5 | 53.3 | 74.2 |
| **6** | 22 | 28.6 | 33.3 | 38.3 | 45.8 | 52.3 | 59.6 | 81.9 |
| **9** | 25.5 | 32.8 | 38.1 | 43.6 | 51.7 | 58.8 | 66.7 | 90.8 |
| **12** | 28.4 | 36.3 | 41.8 | 47.7 | 56.4 | 63.9 | 72.3 | 97.9 |

*Note *: The 0.1% AEP frequency event has had rainfall depths calculated by extrapolation from the depth values in the FSU DDF grid and the estimates provided for the various rainfall frequencies (50% - 0.5% AEP).*

[4] FSU Technical Research Report Volume II Rainfall Frequency

## 6.2 Design Rainfall Profiles

Design rainfall sums are disaggregated over the Flood Studies Report (FSR) summer and winter rainfall profiles[5] depending on an assessment of the likely seasonality of a flood event within the sub-catchment in question. As there are reports of flooding (see Table 1.2) which occurred during the summer and winter months, both summer and winter profiles must be tested within the pluvial models/calculations to determine the most critical seasonal storm profile. The FSR summer and winter rainfall profiles across which the rainfall sums are applied are shown in Figure 6.1.

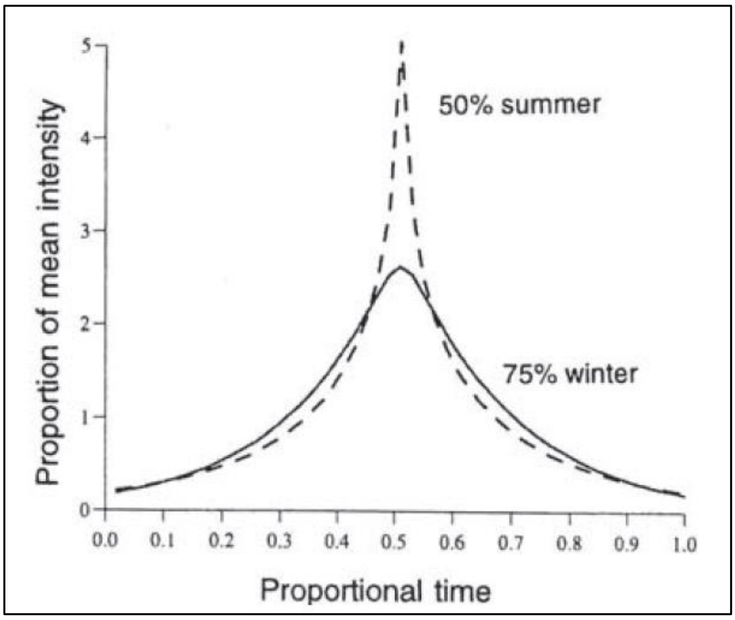


**Figure 6.1 FSR Rainfall profiles, extracted from FEH, Volume 2, Chapter 4 (1999)**

Where the pluvial analysis is used to test behind defence drainage, the critical event duration and season may need to be considered against the fluvial critical storm duration and seasonality where the critical mechanism is locked out of the drainage system due to high levels in the receiving river/watercourse.

The range of event durations will be tested within the model to determine the critical event in relation to the sub-catchment / drainage system and the full range of current and future scenario design events run for that duration.

[5] See Flood Estimation Handbook Volume 2, Chapter 4 (Institute of Hydrology, 1999)

# 7 FUTURE SCENARIOS

There are a number of potential future changes which could impact the effectiveness of any flood management measures proposed. It is prudent that the potential impacts are identified and quantified such that effective planning and design for adaptation can be accommodated. The adjustments which will be applied to the design flow estimates are outlined in 'Flood Risk Management, Climate Change Sectoral Adaptation Plan' (OPW, 2019)[6] and are reproduced in Table 7.1.

Rates of urbanisation were assessed under the CFRAM Study and are reported in the Unit of Management 01 (UoM01) Hydrology Report. The River Finn main catchment is predominantly rural however the smaller tributary catchments are partially urbanised and susceptible to significant future urbanisation if the settlement expands. Therefore, it is predicted that within these smaller, partially urbanised catchments there will be a greater impact on future flood flows. The growth rates for two scenarios: Mid-Range and High-End Future Scenarios (MRFS and HEFS, respectively), are shown in Table 7.1. These growth rates will be applied to the catchment descriptors describing urban fabric within the relevant catchment for Castlefinn and the effect on $Q_{med}$ applied through the FSU methods calculated and applied to the design flows.

**Table 7.1 Allowances for Future Scenarios for 100-year time horizon considering urbanisation growth rates reported in the CFRAM Hydrology Report**

| Parameter | MRFS | HEFS |
|---|---|---|
| Extreme Rainfall Depths | + 20% | + 30% |
| Peak Flood Flows | + 20% | + 30% |
| Mean Sea Level Rise | + 500 mm | + 1000 mm |
| Urbanisation | 1% per annum | 2.5% per annum |
| Forestation | Reduce time to peak by 1/6 | Reduce time to peak by 1/3<br>+ 10% on SPR (Standard Percentage Runoff) |

For the River Finn catchment (Cast_03) it is anticipated that peak flows will increase by 22% in the MRFS. 20% of this compound growth[7] is attributable to climate change and a further 1% is attributable to future urbanisation of the catchment which is expected to be low in this rural catchment. For the HEFS, peak flows are projected to increase by 39% with 30% attributable to climate change and 7% attributable to urbanisation.

For the Bridge Burn (Cast_05) catchment it is anticipated that peak flows will increase by 37% in the MRFS. 20% of this compound growth is attributable to climate change and a further 15% is attributable to future urbanisation of the catchment which is expected to be high in this small catchment draining the north-western outskirts of the settlement. For the HEFS peak flows are projected to increase by 133% with 30% attributable to climate change and 79% attributable to urbanisation.

For the Castlefinn watercourse (Cast_12) catchment it is anticipated that peak flows will increase by 88% in the MRFS. 20% of this compound growth is attributable to climate change and a further 57% is attributable to future urbanisation of the catchment which is expected to be high in this small catchment draining the north-eastern outskirts of the settlement. For the HEFS peak flows are projected to increase by 104% with 30% attributable to climate change and 57% attributable to urbanisation.

For the Tievebrack Stream (Cast_09) catchment it is anticipated that peak flows will increase by 20% in the MRFS. 20% of this compound growth is attributable to climate change and a further 0.3% is attributable to

[6] Accessed at: https://www.gov.ie/en/publication/97984b-climate-change-and-sectoral-adaptation-plan/

[7] Note compound growth is calculated by multiplying the components of growth, e.g., 4% growth on top of 20% growth = 1.04 x 1.20 = 1.25, i.e., 25%

future urbanisation of the catchment which is expected to be very low in this rural catchment to the south of the town. For the HEFS peak flows are projected to increase by 31% with 30% attributable to climate change and 1% attributable to urbanisation.

For the Corcullion Stream (Cast_14) catchment it is anticipated that peak flows will increase by 23% in the MRFS. 20% of this compound growth is attributable to climate change and a further 2% is attributable to future urbanisation of the catchment which is expected to be very low in this rural catchment to the south of the town. For the HEFS peak flows are projected to increase by 39% with 30% attributable to climate change and 7% attributable to urbanisation.

# 8 CONCLUSIONS

Castlefinn is located on the lower reaches of the River Finn adjacent to the highly active floodplain of the Finn valley. The upper catchment is steep, impermeable and experiences high sums of rainfall annually. The catchment flattens moving downstream through the Finn valley and at Castlefinn the River is much flatter with backwater from the Foyle a significant contributor to flood risk. The Finn catchment is well gauged and there is high certainty in the flood flows. Certainty decreases moving downstream away from the gauge and as a result of the backwater effects. The water level only gauge at Clady has been used in an attempt to validate the hydrograph response in the lower catchment. The Lifford FRS project modelled the confluence area in great detail and established a synthetic gauge record at the confluence to assist in the assessment of joint probability conditions. The downstream boundary condition for the Castlefinn FRS model is extracted from the Lifford model in light of the comprehensive nature of that analysis and model covering the confluence reaches.

The tributary catchments affecting Castlefinn are characterised by streams draining agricultural land on the valley sides with their catchments becoming partially urbanised on the northern side. There is much higher uncertainty in the flows in these catchments given their ungauged nature and their small size. The presence of a recently installed, small catchment gauging station at Gortinlieve (which was not available at the time of the CFRAM Study) assisted the estimation of $Q_{med}$ and hydrograph response at Castlefinn through pivotal site adjustment using data from a small, geographically close catchment.

## 8.1 Recommendations for Data Collection

The River Finn is well gauged. At the upstream reaches the catchment is well gauged with flow data and at the downstream reaches a water level gauge exists to validate the catchment response. The tributary catchments are ungauged and there is high uncertainty in both their peak flows and hydrograph response and shape. The ungauged nature of the tributaries means there is also no data to determine their coincidence with peak flows on the River Finn. These parameters are likely to be highly important moving to option development where flood volumes may determine the viability of an option. In light of this, it is recommended that some flow gauging is carried out on the small watercourses. The most critical watercourse from this point of view is the Castlefinn watercourse which flows past the CPI centre. It is recommended that flow gauging, either in the form of a full hydrometric gauging station or short-term flow monitoring on a culvert structure, is carried out at the earliest opportunity to validate (or otherwise) the analysis.

The Castlefinn scheme area would benefit from a high-resolution (hourly) rainfall gauge to provide greater certainty in the assessment of pluvial flood risk. This should be considered in conjunction with the Lifford FRS.