Hydrology Report

Ballyhale, Co. Kilkenny

M02151-01_DG01 | January 2021

WATER & ENVIRONMENTAL CONSULTANTS

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DOCUMENT CONTROL

DOCUMENT FILENAME	M02151-01_DG01 Ballyhale FRS - Hydrology Report REV06
DOCUMENT REFERENCE	M02151-01_DG01
TITLE	Hydrology Report
PROJECT CLIENT	Kilkenny County Council
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REVISION HISTORY

Rev. Ref.	Date	Prep	Chk	App	Amendments	Reason for Issue
1	29/07/2020	MR	PS	KS	Original	For Review
2	25/09/2020	MR	KS	DKS	Updated to address OPW Comments	For Review
3	06/10/2020	KS	PS	DKS	Flood source screening assessment added	For Review
4	07/10/2020	KS	PS	KS	Minor amendments	For Review
5	04/11/2020	KS	MR	KS	Updated to address OPW comments circulated 8/10/20 & 14/10/2020	For Information
6	27/01/2021	MR	KS	KS	Updated to address OPW comments circulated 11/11/20 and additional channel survey / river network update	For Information

DISTRIBUTION

Recipient	Revision					
	1	2	3	4	5	6
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EXECUTIVE SUMMARY

The flood relief scheme is centred on Ballyhale village and the Ballyhale and Little Arrigle Rivers previously modelled as part of the South Eastern CFRAM study, undertaken 2012-2016. This report summarises outputs and decision making made as part of the hydrological assessment phase for the scheme.

A search for historic records of previous flood events was undertaken, however only anecdotal evidence was uncovered and no specific dates or evidence (time-stamped photographs, recorded flood levels etc) was found. The catchment is ungauged. There is no sufficiently detailed historic flood record that would permit hydrological or hydraulic calibration of hydrology for the study area.

A screening assessment of flood risk in Ballyhale indicates that recorded flooding historically appears to have been mainly influenced by fluvial flooding and the likely additional effect of culvert blockage. A catchment based fluvial estimation approach is deemed the most appropriate approach for the study area.

Analysis conducted to determine relevant cumulative pluvial catchments to Ballyhale village concluded the size of the surface water subcatchments are assessed to be of insufficient scale to cause significant pluvial risk. Flow contributions from pluvial sources are to be fully represented in the fluvial hydrology.

Local reports of substantial surface water overland flows along the main street were found to originate as out of bank flows from an unmapped upstream tributary of the Ballyhale River and is to be assessed as part of the fluvial hydraulic model.

Physical catchment descriptors have been reviewed and updated where necessary. The hydrological catchment was established through analysis of the best available height data within the area; the updated higher resolution analysis determined that the subcatchments delineated upstream at Ballyhale and Little Arrigle Rivers are generally found to be smaller than the catchment areas derived from the FSU portal and previous studies.

Hydrological Estimation Points (HEPs) were established throughout the model to determine design flows using an estimation of an index flood (Qmed) and the application of a single regional flood frequency curve.

Index flows were estimated using the FSU methodology using the geographically closest gauged pivotal site and compared against legacy methods (FSR, FSSR, IoH124) due to small catchment sizes (<25km^2). FSU methodology was selected due to a relatively lower factorial standard error versus legacy methods and general industry opinion that FSU methodology is the most robust and widely accepted flow estimation method used within Ireland.

Index flows calculated correlate with the CFRAM FSU analysis previously carried out. Index flows were scaled by an areal adjustment factor to represent the updated catchment areas.

Growth curves previously calculated during the CFRAM study were adopted due to the inclusion of additional ‘flood rich’ water years in the CFRAM study which have not been updated to the FSU portal. Cursory analysis of water years data from the EPA HydroNet portal indicate that the additional water years between the CFRAM study and this study are unlikely to significantly distort the dataset.

Hydrograph shape was created using the FSU recommended methodology to apply flows to the model. Due to the similarity in catchment descriptors, a single hydrograph shape was adopted for all flows on the Little Arrigle and Ballyhale Rivers. A separate hydrograph shape was generated for the Knocktopher tributary inflow due to slight variance in catchment characteristics.

Flows will be applied to the model using a combination of lateral (distributed) inflows and point inflows coinciding with tributary confluences indicated by the hydrological analysis.

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1 INTRODUCTION

1.1 Terms of Reference

This Hydrology Report was commissioned by Kilkenny County Council and OPW as the funding authority to summarise outputs and decision making made as part of the hydrological assessment phase for Ballyhale Flood Relief Scheme.

1.2 Statement of Authority

This report and assessment has been prepared and reviewed by qualified professionals with appropriate experience in the fields of flood risk, drainage, wastewater, and hydraulic modelling studies. The key staff members involved in this project are as follows:

- Michael Rea *MEng (Hons)* – Project Engineer with experience in the fields of flood risk assessment, flood modelling, drainage and surface water management design.
- Paul Singleton *BEng (Hons) MSc CEng* – Chartered Civil / Environmental Engineer with particular experience in drainage, SuDS and flood risk assessment, and a recognised industry professional having given industry training in these fields in Ireland and the UK.
- Kyle Somerville *BEng (Hons) CEng* – Associate and Chartered Engineer specialising in the fields of flood risk assessment, flood modelling, drainage and surface water management design for public and private sectors.

1.3 Purpose

The objective of this hydrology report is to provide detail on work undertaken to characterise flood hydrology, which will be utilised in hydraulic modelling to inform and assess the Ballyhale Flood Relief Scheme (FRS).

This report records the outcome of:

- a background review of information, including the previous CFRAM study,
- establishment of the hydrological setting and potential for influence of fluvial hydrology by surface water (pluvial) sources, groundwater, urban drainage, and artificial sources.
- hydrological flood analysis and design flow estimation, and
- project risks associated and sensitivity testing to be undertaken.

Design flows determined by this assessment will be taken forward as inputs for the hydraulic modelling.

2 STUDY AREA

2.1 Study Location

The study location which incorporates Ballyhale village and a portion of the Ballyhale and Little Arrigle Rivers is shown on the following figure.

Ballyhale was previously modelled as part of the South Eastern CFRAM study (published final 2016).

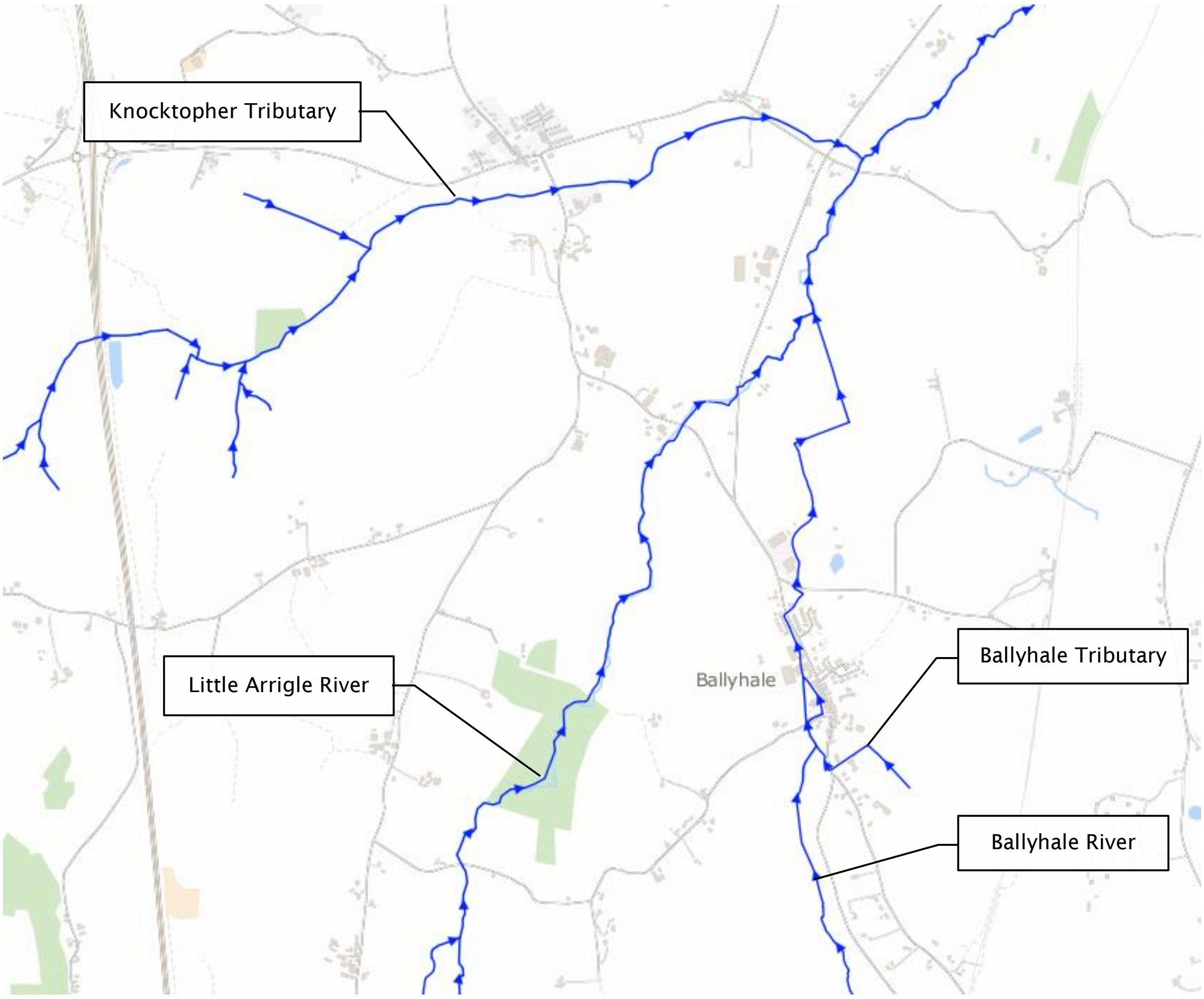


Figure 2-1 FRS Study Location

As shown in Figure 2-2, the Ballyhale River flows through the centre of Ballyhale village to the rear of properties on the main street and is partially culverted / built over for much of its urban reach. A secondary channel bifurcates immediately upstream of the village, flowing parallel to the west of the main channel and is anecdotally understood to form part of a flood relief scheme from the mid-20th century. No further background information to this diversion was made available.

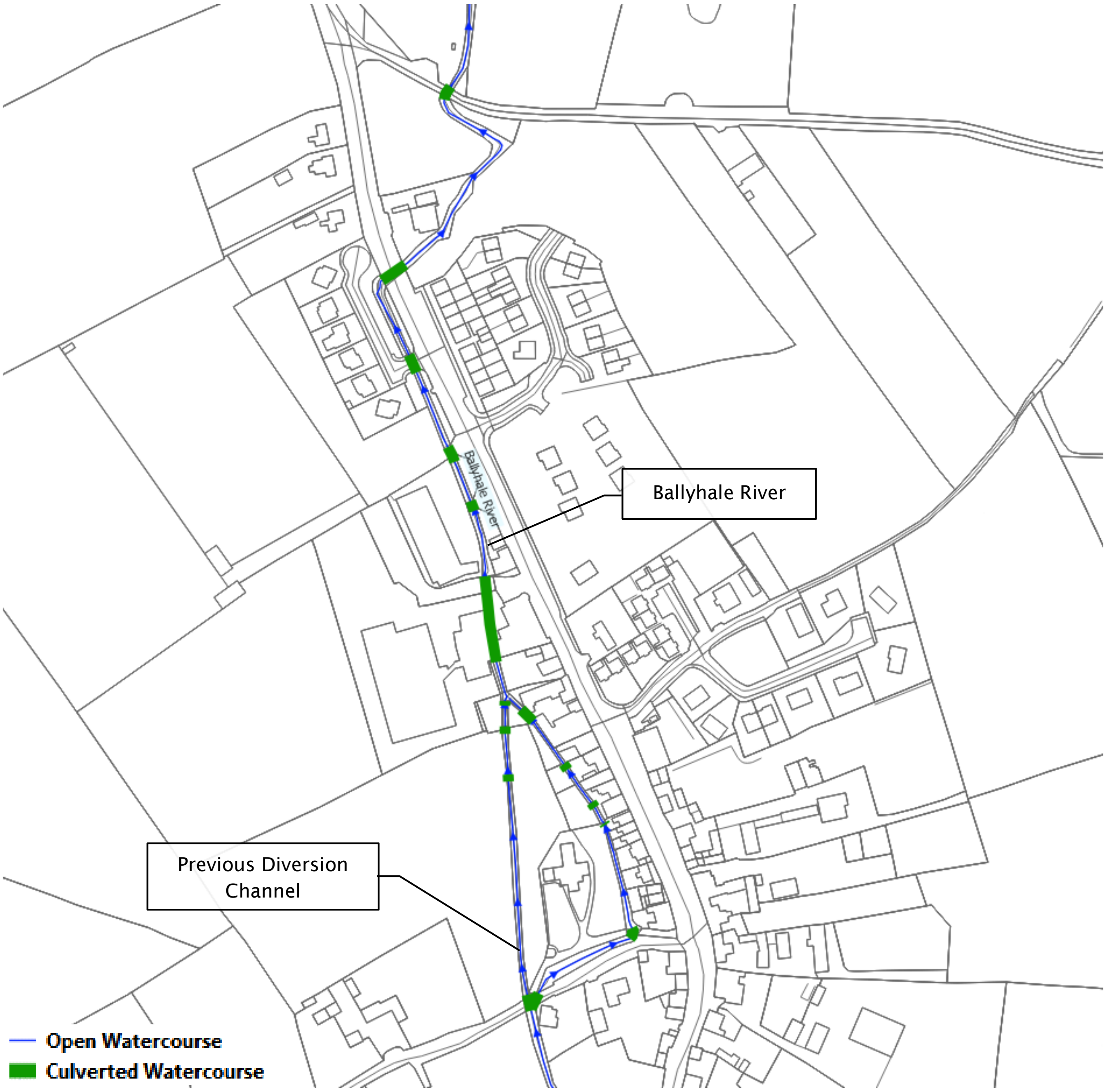


Figure 2-2 Ballyhale River Structures

2.2 Proposed Hydraulic Model Extent

While not subject to detailed discussion in this report; it has been pertinent to identify at the outset the intended hydraulic model extent in order to define the limits of the hydrological analysis.

The model extent was carefully sited to ensure:

- Coverage within Ballyhale village and all key receptors.
- To provide sufficient fall from the main area of interest to ensure water levels cannot be artificially influenced by downstream boundary conditions.
- The upstream and downstream boundaries of the model are situated in places predicted to contain flooding in channel for model stability.
- To incorporate the upper Little Arrigle River (not previously modelled as part of the CFRAM study), due to its potential to be utilised as part of the flood relief scheme.
- The downstream model extent was extended to provide sufficient distance from the Knocktopher tributary for stability and to assess the impact of any scheme on water levels downstream.

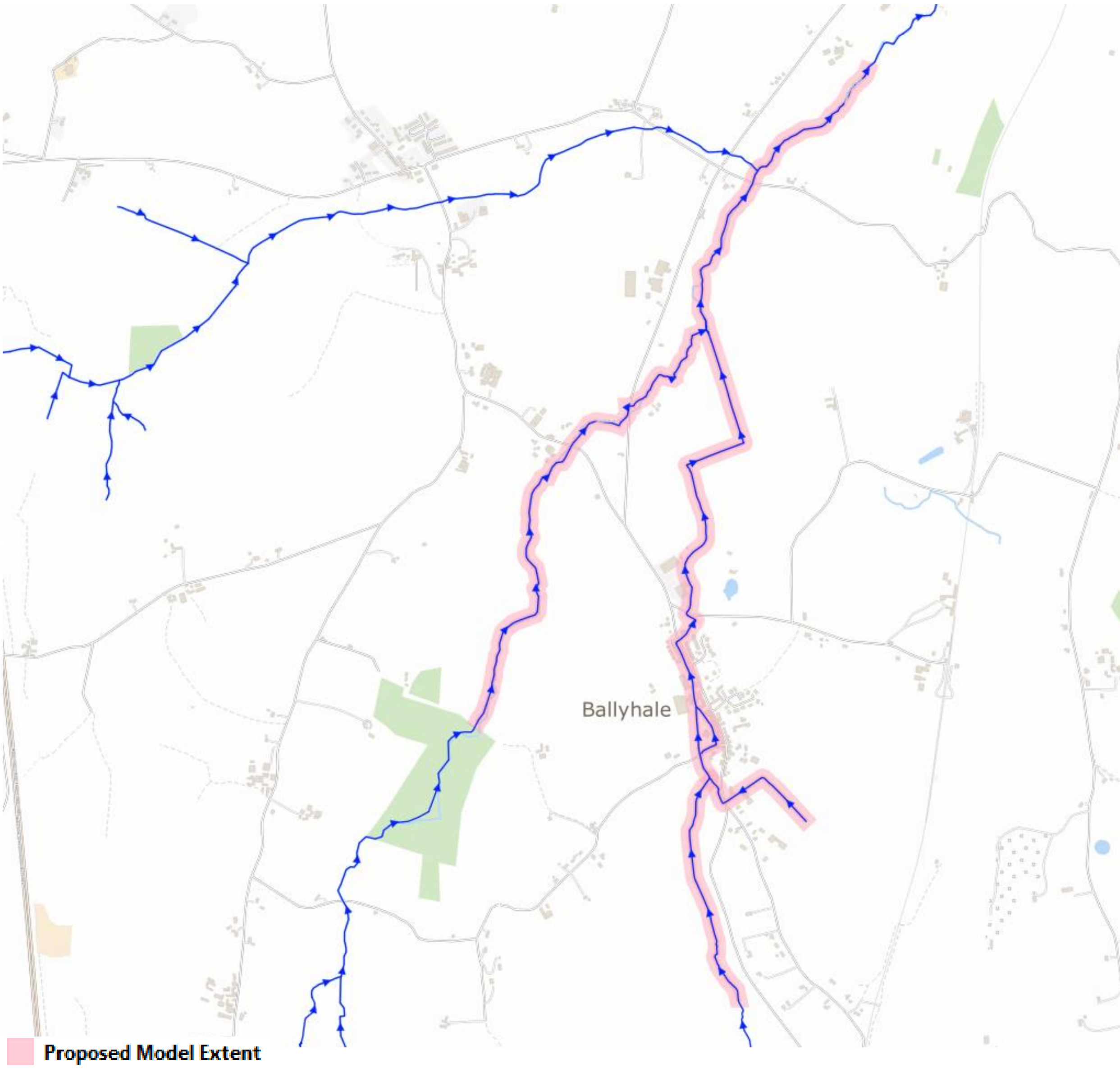


Figure 2-3 Proposed Hydraulic Model Extent

3 REVIEW OF AVAILABLE DATA

3.1 CFRAM Hydrology Data

Ballyhale was previously modelled as part of Hydraulic Area 15 in the south eastern CFRAM study[1], undertaken 2012-2016. The Ballyhale model includes the Ballyhale River and the downstream portion of the Little Arrigle River to its confluence at the River Nore.

The catchment is ungauged. CFRAM hydrology was estimated solely using the FSU methodology for ungauged catchments, deviating from initial intended methodology of using MIKE NAM (runoff routing) modelling for the head of reach and IoH Report 124 for tributaries as proposed in the inception report.

3.1.1 CFRAM Index Flows

The FSU 7-variable ungauged catchment descriptor equation was used to calculate an estimate of the Index Flood flow at all HEPs. No rainfall run-off models were developed as part of the CFRAM study due to a lack of gauged data on the watercourse to calibrate the index flow. No gauging stations have been installed on the Ballyhale or Little Arrigle rivers since the CFRAM study therefore due to the lack of calibration data, development of a rainfall run-off model is not considered a feasible option for this study.

The estimate was adjusted using a gauged pivotal site. A review of pivotal site options indicated a trend for upwards adjustment of the index flows. The FSU hierarchy for selecting pivotal sites is as follows:

1. Downstream gauged catchment.
2. Proximal gauged catchment / geographically closest.
3. Most hydrologically similar.

Station 15001 (Annamult) was selected on the basis of being geographically closest (i.e. second in the hierarchy). Review of the CFRAM hydrology report does not give a rationale for discounting the downstream gauged catchment (Station 15006 Brownsbarn), however is presumed to be due to the large catchment size (2400km^2) with resulting hydrological dissimilarity in comparison to the subject site.

3.1.2 CFRAM Growth Curves

Growth curves were subsequently developed in accordance with the methodologies set out in the FSU studies. Annual maximum (AMAX) data was provided by the OPW and EPA for up to 2009. It is noted that the publicly accessible FSU portal (which is similarly the limit of data available for this project) uses AMAX data up to 2004.

A summary of flows used in the CFRAM Study are detailed in Table 3-1 and their application to the Ballyhale model is shown on Figure 3-1.

Flows were applied to the model at the upstream extent and where tributaries enter the modelled channel. Additional 'top up' flows were applied along the length of the modelled watercourse as lateral inflows.

Table 3-1 CFRAM Flows

CFRAM Hydrology Estimation Points	AREA (km^2)	Qmed	Flows for AEP							
			50% (2)	20% (5)	10% (10)	5% (20)	2% (50)	**1% (100)**	0.5% (200)	0.1% (1000)
15_1358_3_RPS	10.81	1.9	1.9	2.62	3.14	3.71	4.57	**5.34**	6.21	8.79
15_1182_7_RPS	13.19	1.73	1.73	2.37	2.85	3.35	4.12	**4.80**	5.57	7.84
15_1212_7	15.09	2.24	2.24	3.22	3.95	4.77	6.03	**7.16**	8.49	12.53
15_1337_12_RPS	10.1	2.57	2.57	3.61	4.39	5.24	6.54	**7.70**	9.05	13.09

[1] RPS. (2016). Southern Eastern CFRAM Study HA15 Hydrology Report. Belfast: OPW.

CFRAM Hydrology Estimation Points	AREA (km²)	Qmed	Flows for AEP							
			50% (2)	20% (5)	10% (10)	5% (20)	2% (50)	**1% (100)**	0.5% (200)	0.1% (1000)
15_1814_4_RPS	63.72	10.09	10.09	13.09	15.16	17.30	20.39	**22.98**	25.85	33.75
Top-up between 15_1358_3_RPS & 15_1814_4_	14.53	2.53	2.53	3.28	3.79	4.33	5.10	**5.75**	6.47	8.45

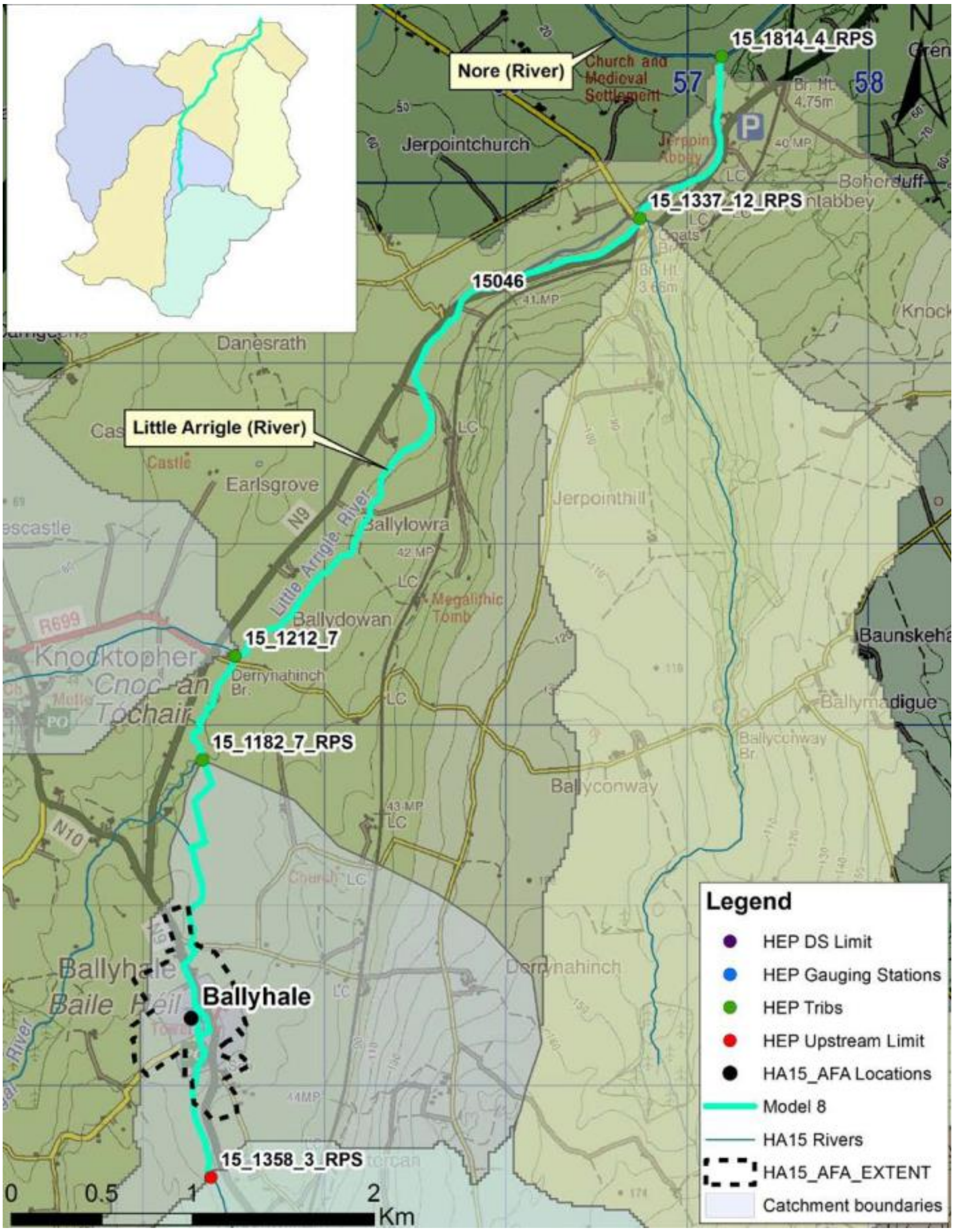


Figure 3-1 CFRAM Hydrology Estimation Points

3.2 Historic Flood Data Analysis

A search for historic records of previous flood events was undertaken to determine new information over and above that considered by previous studies.

3.2.1 FloodInfo

One report of flooding was documented on floodmaps.ie dated November 2000 stating a recurring flood on the road between Ballyhale and Mullinavat[2], however no specific information relating to fluvial flooding of the Ballyhale or Little Arrigle rivers was mentioned.

3.2.2 Ballyhale Local Area Plan

The Ballyhale Local Area Plan[3] 2004 stated that the flooding of the Ballyhale River has occurred a number of times in the 10 years up to time of publication, and has caused flooding on the Station / Kiltorcan Road at the church and to the rear of buildings on the east of main street.

3.2.3 Site Walkover / Observations

A site walkover of the village indicated 2 properties along the main street have had flood barriers installed. It was noted however that multiple properties threshold levels were located at a similar level to the road with no freeboard or kerb to direct road run-off away from property entrances. It appears the primary purpose of the flood barriers is to defend against overland flooding at street level since they are at the front of the property.

A large grate was observed at a laneway (known locally as 'Sheff's Lane') beside a public house on the main street, recently installed / upgraded to capture a substantial surface water flow route.

3.2.4 Local Residents / Business Owners Accounts

Responses from residents / business owners regarding flooding within the area collated during site walkover and subsequent discussions arising from enquiries and questionnaires. The following details responses received to date:

Table 3-2 Historical Flooding Reports

Report	Event Date	Details	Likely Flood Source / Mechanism
Verbal account 1.	November 2000	A commercial unit at the Arrigle Business Park (location 1) was subject to internal flooding.	Fluvial / Blockage of Downstream Culvert.
Verbal account 2.	November 2000	A commercial unit (vehicle repair shop) backing onto the River (location 2) from the main street was externally and internally affected, with flood depths c. 50cm at the side of the property and 30cm internally. A downstream culvert was reported to be blocked which may have exacerbated / caused the flooding. Flooding entered the property from a rear door.	Fluvial / Blockage of Downstream Culvert.

[2] Kilkenny County Council. (9th November 2000). DOE Circular Letter EP 2/00 - Assessment Reports on Severe Flooding.
[3] Kilkenny County Council Planning Department. (19th July 2004). Ballyhale Local Area Plan. Available from: https://www.kilkennycoco.ie/eng/Services/Planning/Development-Plans/Local%20Area%20Plans/Adopted_Local_Area_Plans/Local_Area_Plan_Ballyhale.html. [Accessed: 2/9/2020].

Report	Event Date	Details	Likely Flood Source / Mechanism
Verbal account 3.	November 2000	A resident whose house is indicated on Main Street (location 3) advised that flooding came from the rear of the house (Ballyhale River), and not from the main street. The resident had a flood barrier installed to the front of the house but advised that this was removed to allow flood waters to subside. Internal flood depths within the house rose to approximately 0.3m. It was also reported the storm sewers in the main street were backing up and flooding onto the street. It was of the residents opinion that the bridges crossing Main Street (location 4) and Station Road (location 5) were a leading cause of the river and surface water backing up as a result of previous improvements together with newer culverts and obstructions.	Fluvial
Verbal Account 4.	November 2000	A resident who lives at the corner of Main Street / Chapel Lane reported manholes within the main street lifting as the storm water could not get into the river. A substantial flow path of surface water flow originated from 'Sheffs Pub Lane' (location 6) and inundated the street. Flows originating from 'Sheffs Pub Lane' tended towards Chapel Lane and re-entered the river; some flows tended down Main Street and re-entered the river at Andy's pub (location 8). In very extreme events flows can continue down street and re-enter river at Prendergast tyres Historically flows from Sheffs Lane flowed in-channel adjacent to the school, however culverts installed to facilitate this are reported to frequently block during dry periods and flows bypasses these and pass directly onto Main Street via Sheffs Lane.	Fluvial
	1947	There was a significant fluvial flood event in 1947. The bifurcation / secondary channel around the church was constructed shortly after this.	Fluvial
	1970	There was a significant fluvial flood event in 1970 where all dwellings along the western side of Main Street were reported to have been affected.	Fluvial
	Unknown Dates / General Comments	It was reported that the graveyard and church previously flooded with estimated water levels to the top of the wall at Chapel Lane downstream (location 7). Flood waters had entered the church grounds through the stile.	Fluvial
		A house opposite the GAA club entrance (since demolished / replaced by the Brookfield development – location 9) was affected by internal flooding of c. 45cm.	Fluvial
		Flooding tends to first occur at the Station Road culvert then work way back up through village. Angle of new culvert/bridge on Station Road results in flows 'circulating' at its entry without passing through. (Location 5)	Fluvial

Report	Event Date	Details	Likely Flood Source / Mechanism
		There have been flood events where overland flows traverses the fields to rear of properties and across the properties onto Chapel Lane (location 10).	Fluvial
		The channel at Chapel Lane has gradually been lowered and road level has been risen. It was noted that previously cars could be driven directly into river channel (to wash) at Location 7.	N/A
		Arrigle View house at bridge (location 11) and other properties on Chapel Road have previously flooded multiple times.	Fluvial
		A tributary of the Ballyhale River south of the village (flowing adjacent to the primary school) is noted to flood at a 90 degree bend in the watercourse (location 12). Observations and reports indicate the channel downstream of this point is prone to blockage, exacerbating out of bank flooding at this location. Out of bank flooding from this point in the watercourse tends to flow overland onto 'Sheffs Lane', entering Main Street in the village at location 6 and is likely the most significant contributor to flooding observed within the main street.	Fluvial

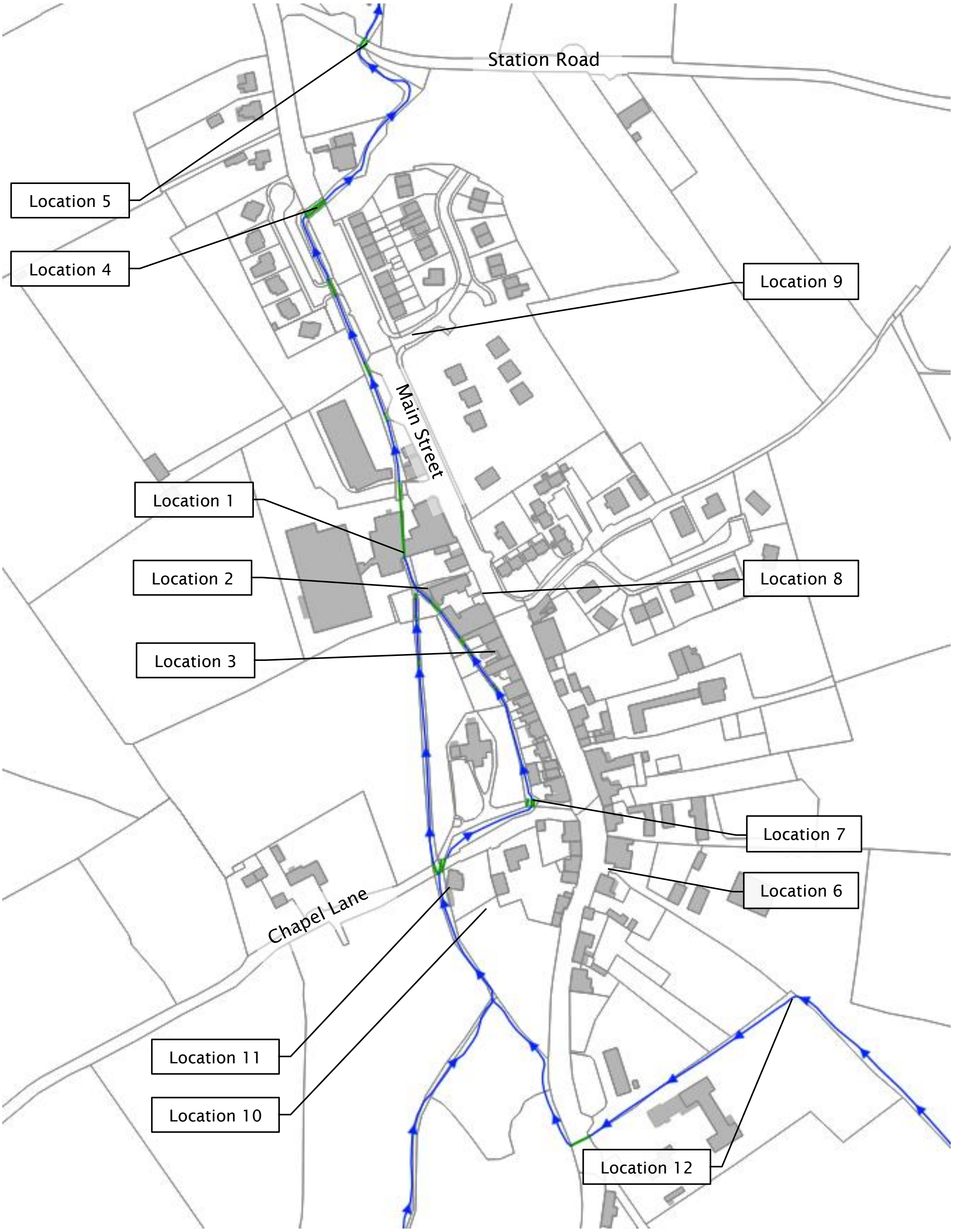


Figure 3-2 Historic Flooding Locations

3.2.5 Summary

No officially reported flood records exist for the Ballyhale area. Historical flooding accounts from residents relate to mainly fluvial, overland pluvial and inadequate stormwater drainage. However, none of the accounts are sufficiently detailed to permit calibration or estimation of hydrology for the Ballyhale or Little Arrigle Rivers.

Anecdotal evidence from local residents / stakeholders indicate at least one previous flooding incident in the village in November 2000 with a further single report of flooding in 1947 after which a second channel was installed at the church. Flooding may have occurred at other times but no specific dates were able to be ascertained. Approximate locations of flooding and depths have been obtained from mainly anecdotal reports.

The November 2000 event appears to have been primarily a fluvial flooding event and may also have been influenced by structure blockage. On street flooding from 'Sheff's Lane' has been investigated to originate from out of bank flooding from an unmapped tributary of the Ballyhale River. The hydraulic model exercise will seek to verify hydraulic model results against anecdotal records and will investigate the sensitivity of structures to blockage.

Daily total rainfall records from the nearest Met Eireann rain gauge (Thomastown, 6km north of Ballyhale) were obtained for the historical flood event which indicated a total rainfall of 53.9mm on 5th November 2000 – the most likely date to coincide with the flooding.

A (closed) station in Kilkenny, approximately 20km from Ballyhale is the only station with more detailed (hourly / sub-hourly) records, however the total rainfall was significantly less (17.2mm) for the period, indicating it may have been a more localised heavy rainfall event. Available rainfall records are insufficiently detailed to allow estimation of a rainfall event or flood magnitude, or to allow replication of the flood event and hydraulic model validation.

3.3 Arterial Drainage

Review of OPW arterial drainage schemes[4] indicate there are no arterial drainage schemes or benefitting lands within the model catchment.

[4] OPW Floodinfo.ie. (2020). OPW Arterial Drainage Schemes. Available from: https://www.floodinfo.ie/. [Accessed: 2/9/2020].

4 HYDROLOGICAL SETTING

4.1 Catchment Boundaries

The hydrological catchment draining to the downstream limit of the area of interest (i.e. the proposed model extent), dictated by topography and excluding the influence of any arterial or surface water drainage scheme was established through analysis of the best available height data (5m DTM + 2m LiDAR) in gridded format to determine the flow direction and accumulation to each grid cell to delineate the natural catchment.

Topographical / flow route analysis and delineated catchment for the study area is shown on Figure 4-1.

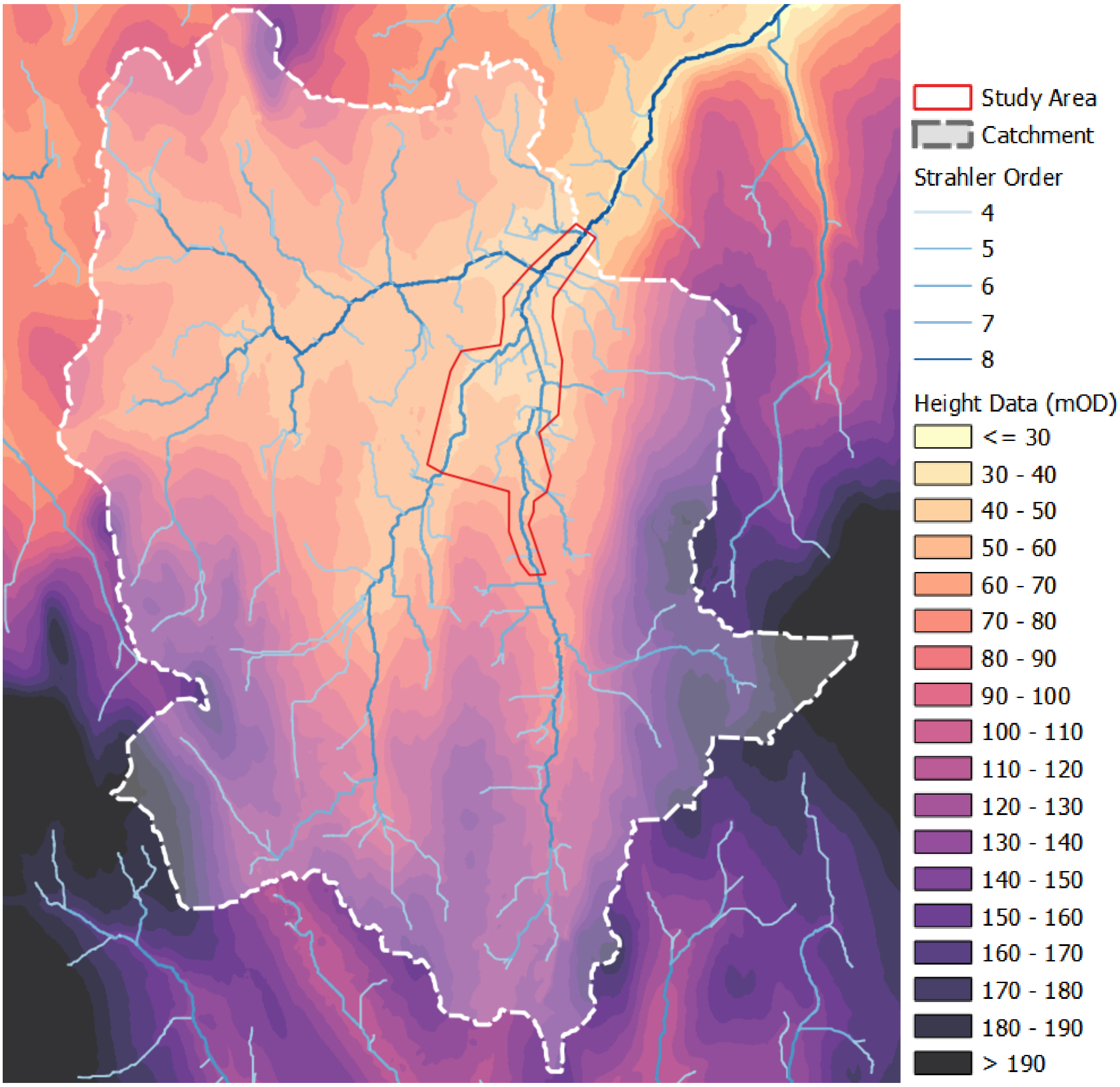


Figure 4-1 Topographic Data and Flow Accumulation Analysis

Catchment boundaries have been verified where possible using background mapping, contour mapping, and site observations.

Given that the catchment is ungauged and the driver for the FRS is underpinned by the CFRAM model exercise, it was deemed initially pertinent to compare and validate catchment boundaries with CFRAM hydrology.

Sub-catchments were delineated for the four main hydrological estimation points adopted by the CFRAM study to allow comparison with the existing CFRAM analysis corresponding FSU catchments. Sub catchment area characteristics are detailed in Table 4-1.

Table 4-1 Catchment Comparison

FSU HEP Catchment	FSU Catchment (km^2)	CFRAM Catchment (km^2)	McCloy Catchment (km^2)
15_1358_3 – Ballyhale U/S Extent	10.3	10.8	9.6
15_1182_7 – Little Arrigle River / Ballyhale Confluence	13.1	13.2	12.1
15_1212_7 – Knocktopher / Little Arrigle River Confluence	15.1	15.1	16.9
15_1814_4 – Little Arrigle / Nore River Confluence	63.2	63.7	64.4

In summary, the updated higher resolution analysis has found that sub catchments delineated upstream at Ballyhale and Little Arrigle Rivers are slightly smaller than the FSU / CFRAM catchments, however the total catchment to the Little Arrigle confluence with the River Nore is larger.

Catchments derived are shown on the following Figure 4-2, with FSU portal catchments overlaid for comparison. Similar CFRAM catchments estimated to common HEPS were previously shown on Figure 3-1.

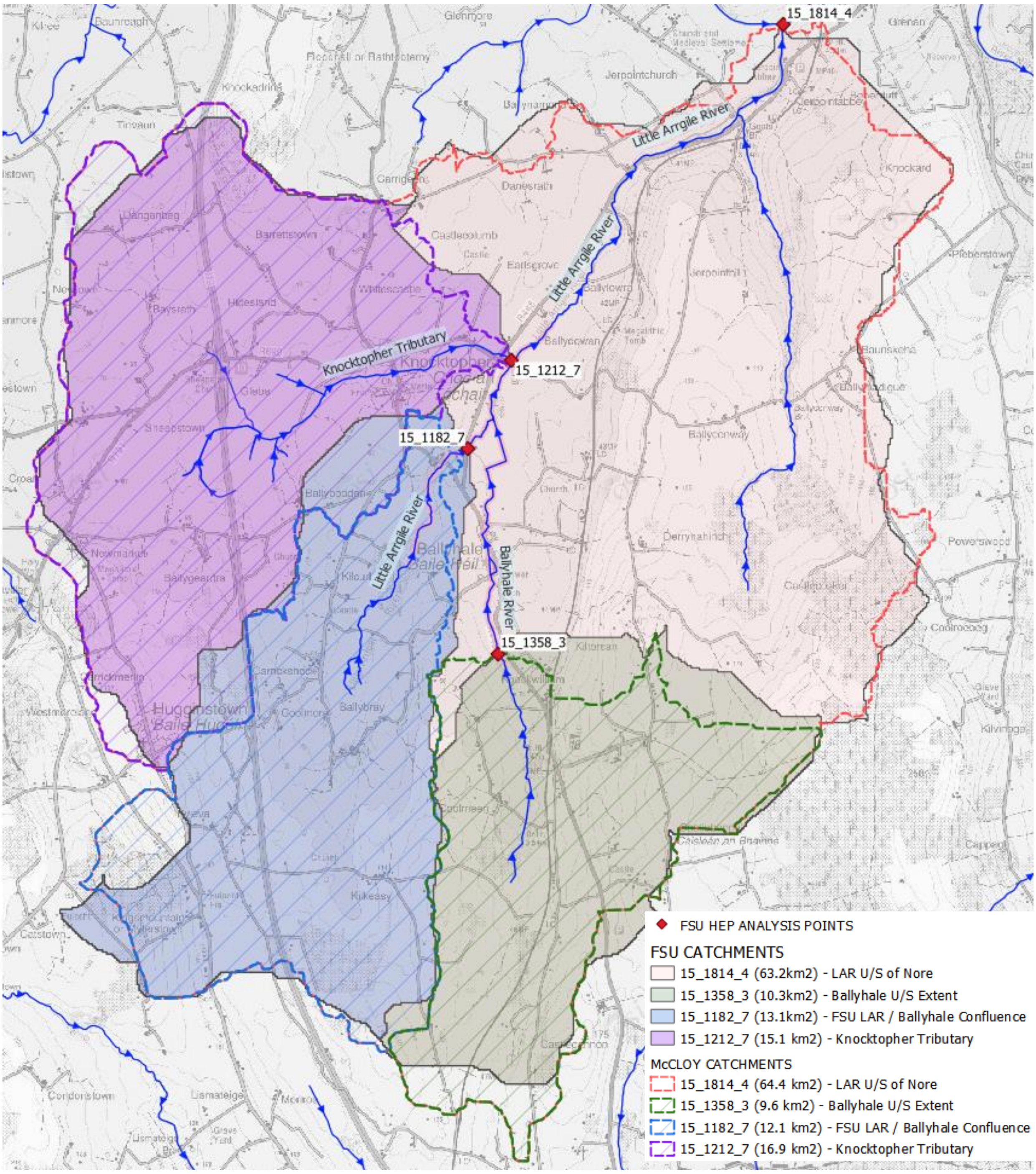


Figure 4-2 FSU Catchments vs McCloy Catchments

4.2 Flood Studies Update Physical Catchment Descriptors

Catchment descriptors were derived from the FSU dataset. Physical catchment descriptors have been verified where possible against the recalculated catchment boundaries, background mapping and soil data.

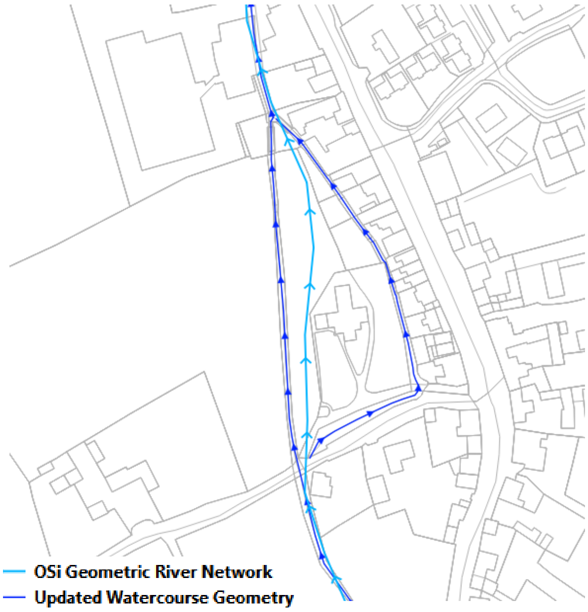
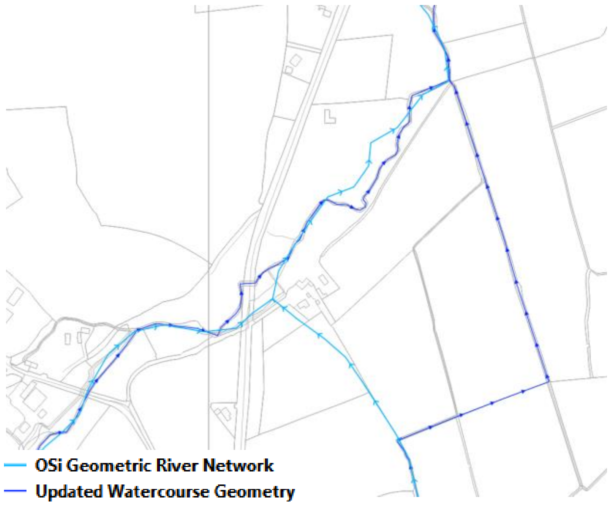
A screening analysis confirmed that slight changes in sub catchment areal extent were insufficiently large to cause any significant changes in underlying physical catchment descriptors for use in later statistical analyses.

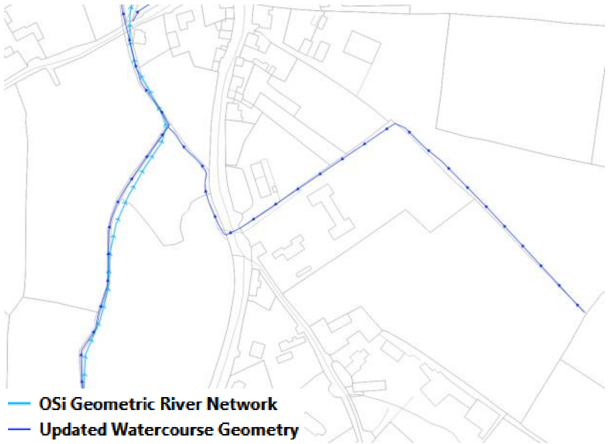
4.3 River Network

The most recent version of the OSi geometric river network was downloaded and reviewed against CFRAM outputs, OSi Prime2 mapping, and stream classification analysis on best available height data.

There was low confidence in the OSi Geometric River dataset to use it as a basis for the hydraulic model, therefore a new river centreline was digitised based on Prime2 Mapping, verified on site walkover and with river survey information. Key discrepancies are noted in Table 4-2.

Table 4-2 River Network Discrepancies

Description	Location
OSi river network dataset does not take into consideration the bifurcation of the Ballyhale river within Ballyhale village. The watercourse geometry was updated per OSi mapping. The discrepancy has no major impact on the physical catchment descriptors for the catchment.	
The location of the Ballyhale / Little Arrigle River confluence was shown to be incorrect in the OSi river dataset. The watercourse was updated based on OSi mapping, CFRAM study results, and LiDAR stream analysis. As a result of the discrepancy, catchment size to be slightly altered to represent the change in hydrology estimation point at the confluence.	

Description	Location
OSi river network dataset does not include a tributary to the Ballyhale River upstream (south) of the village. The watercourse was surveyed and ground truthed on site and shown to flow north westerly towards Ballyhale and 'Sheff's Lane' before turning at a sharp 90 degree bend to flow south west adjacent to the school. The watercourse is culverted under the main street and joins the main Ballyhale River c. 100m downstream. The watercourse geometry was updated based on site observations and survey information. The watercourse has a catchment size of c. 1.3km^2 which will influence the catchment size to the Ballyhale River upstream of the village.	

5 FLOOD SOURCES SCREENING

5.1 Purpose

This chapter is an evaluation of sources of flooding and their influence on the hydrological setting. It will screen sources of flooding and their significance in relation to the estimation of fluvial hydrology at Ballyhale.

5.2 Groundwater / Hydrogeology

Groundwater flooding occurs when water stored beneath the ground rises above the surface of the land. In Ireland, the most extensive form of groundwater flooding is related to prolonged rainfall causing water table rise in limestone lowland areas, primarily in the west of the country. A desktop review was completed to assess the influence of groundwater on the Study Area. This review was complete using available local data and national mapped datasets.

5.2.1 Bedrock Aquifers

The hydrological basin draining to Ballyhale lies over the Carrigmaclea Formation (conglomerate & sandstone) and Kiltorcan Formation (sandstone & mudstone) which are classed as regionally important aquifers dominated by flows in fissured bedrock

Shortly north of Ballyhale the Knocktopher and Little Arrigle Rivers are underlain by the Porters Gate Formation (sandstone, shale & thin limestone) and the Ballymartin Formation (limestone & calcareous shale)The north of the Knocktopher Tributary catchment is underlain by the Ballysteen formation (limestone and shale) which are locally important aquifers which are moderately productive only in local zones.

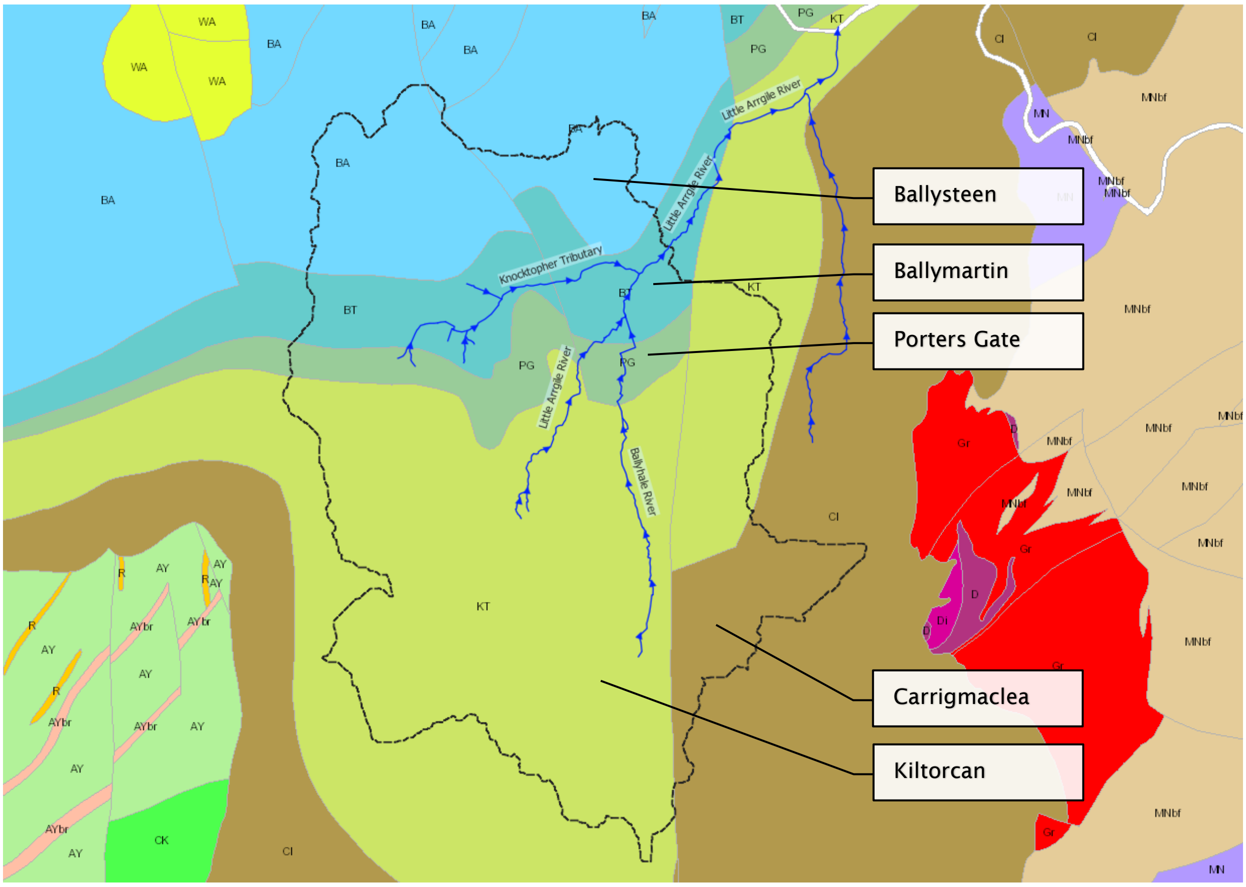


Figure 5-1 Model Catchment vs GSI 100k Bedrock Lithology

5.2.2 Superficial Cover

Much of the basin is covered by till derived from sandstones and limestones. Superficial alluvium deposits coincide with the Little Arrigle and Knocktopher Tributary rivers. Areas of exposed bedrock / no cover are mapped over higher ground. Subsoil permeability is mapped as low to medium where cover is present.

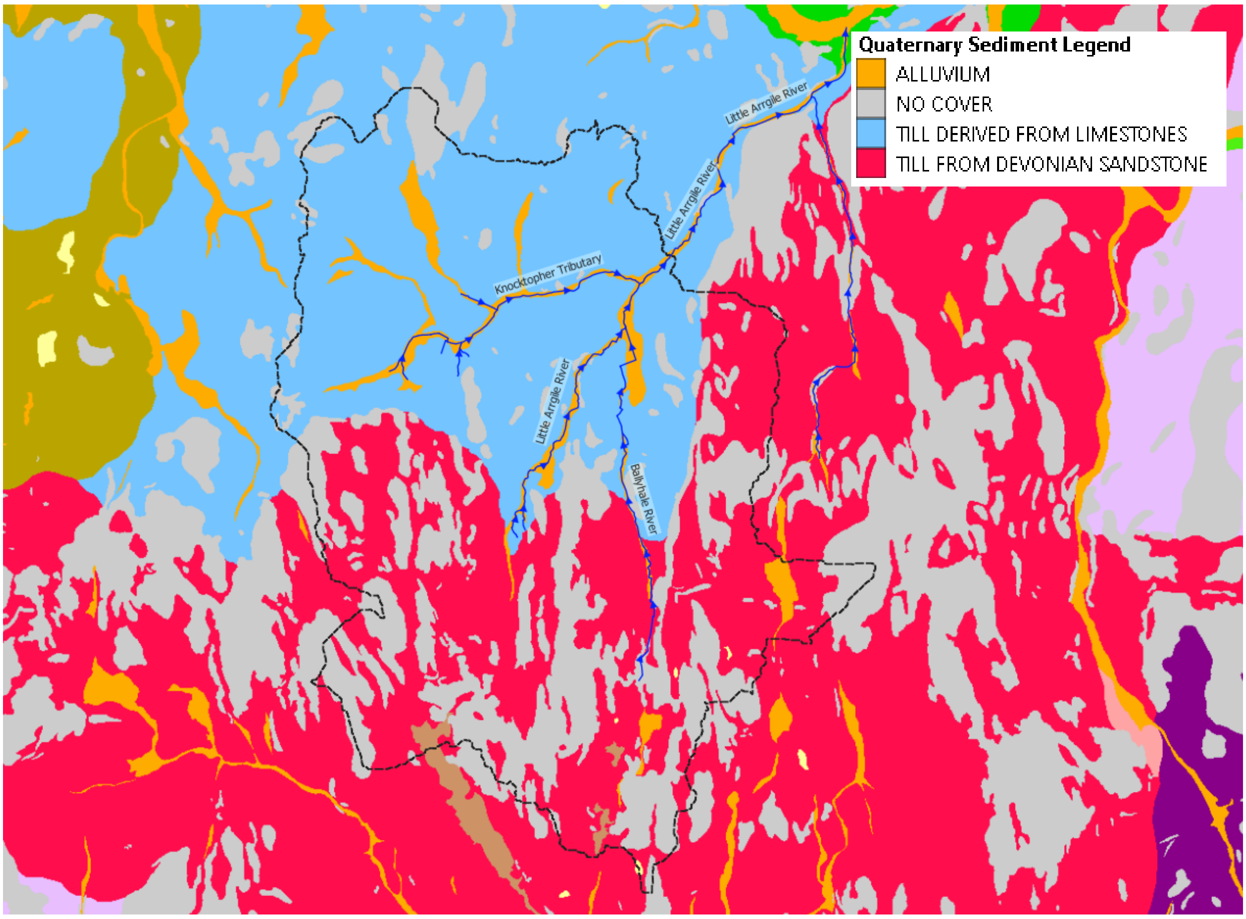


Figure 5-2 Model Catchment vs GSI 100k Quaternary Sediments

5.2.3 Karst Features

The GSI karst feature database indicates no karst features or known flows within the hydrological catchment subject to assessment.

5.2.4 Springs

Review of the GSI borehole and springs database inferred no springs within the hydrological catchment subject to assessment that would suggest groundwater at or near surface. Boreholes and wells are prevalent (consistent with the locally important aquifer resource) but records tend to indicate that groundwater is at depth.

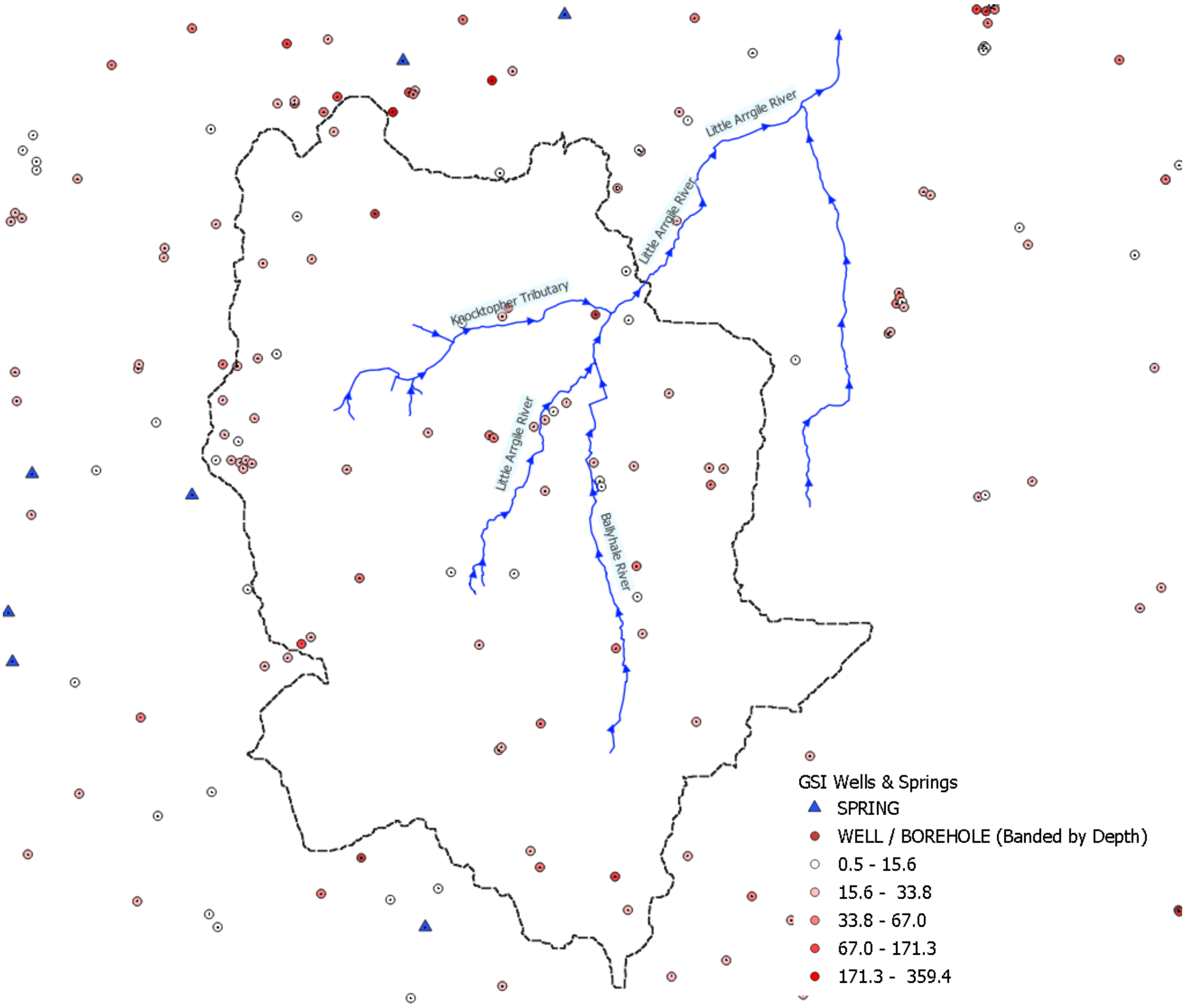


Figure 5-3 Model Catchment vs GSI Wells and Springs Database

5.2.5 Groundwater Flood Database

Review of the GSI predicted groundwater flooding database indicates no areas of predicted flooding proximal to the area of investigation.

5.2.6 Summary

From a review of the available information, anecdotal records and inspection of the catchment there is no evidence of significant groundwater influence on fluvial hydrology in the catchment. Ground conditions in conjunction with topography is likely to cause the risk of clearwater (above ground) or below-ground groundwater flooding to be insignificant in the Ballyhale area.

5.3 Pluvial / Surface Water

The catchment(s) that could contribute direct pluvial overland flooding to sensitive receptors within Ballyhale village have been evaluated by determining the extents of the upstream hydrological catchment and associated significant flow paths between the L8256 at its bridge over the Ballyhale River, and the L8253 where it crosses the Ballyhale River at the downstream extent.

The analysis used a GIS evaluation of the terrain model formed from best available OSI LiDAR data and site won topographic and river survey. The algorithm uses a Rho-8 type "rolling ball" hydrological analysis to determine key flow paths and drained areas.

The analysis determined that the relevant cumulative pluvial catchment draining is 0.37 sq. km, of which comprises undeveloped green space and Ballyhale GAA west of the village (0.2 sq. km) and the village itself

(0.17 sq. km). Catchments and predicted flow paths are shown on the following figure. The flow path analysis is sensitive to aspects such as structures, kerbs & street furniture whereby overland flow may be diverted to run in the main street where it is unable to enter the river channel.

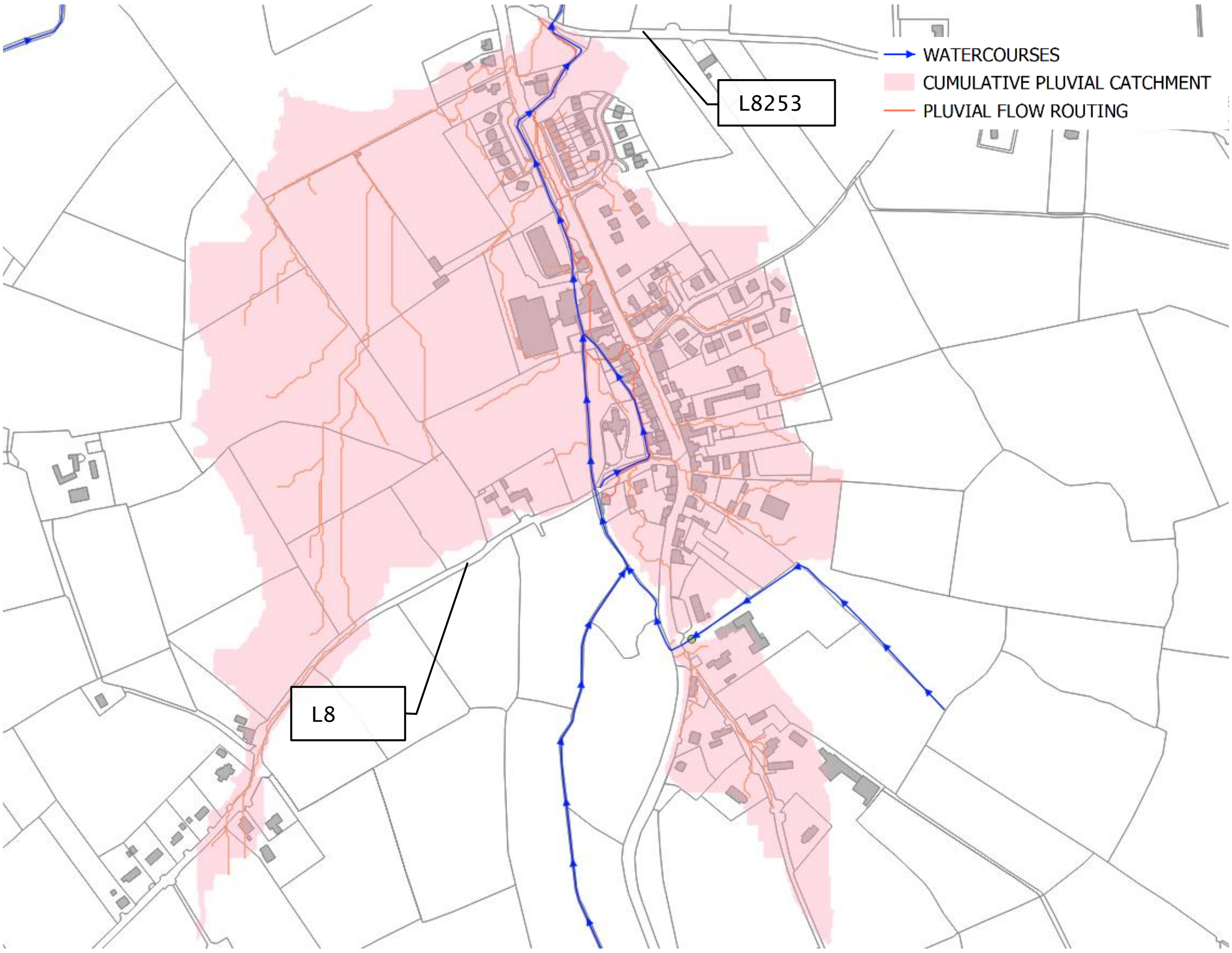


Figure 5-4 Pluvial Catchment Analysis

The size of the surface water subcatchments are of insufficient scale to cause significant pluvial flood risk.

The surface water subcatchments all tend to the Ballyhale watercourse. The overall fluvial model catchments include these subcatchments and the flow contributions from pluvial sources have been fully represented in the fluvial hydrology by the method described at Section 0.

5.4 Urban Drainage

Information compiled to date indicates that there is no substantial surface water drainage network present in Ballyhale (the drainage appears to be limited to small gully leads/stone shore). Any small-scale network is likely to be of insufficient scale to significantly affect routing or distribution of fluvial inflows or pluvial flow paths.

There is no evidence of significant urban drainage influence on fluvial hydrology in the catchment. Overland flows and paths from pluvial flood analysis have been assessed for flood flow estimation.

5.5 Blockages

Information gathering (Section 3.2) and observations during site walkovers tends to indicate that fluvial flooding has previously been influenced by blockages in channels and at culverts. A description of blockage locations noted through historical reports or assessed as significant within Ballyhale are detailed in the following table.

Table 5-1 Potential Blockage Locations

Ref	Location	Description
1	Chapel Lane Bridge	Site walkover informed land use upstream likely to create blockage debris, first bridge / structure where debris has an opportunity to get trapped before entering the urban area where there is less vegetation. Metal pipes traverse the opening on the upstream side which is likely to promote blockage.
2	Garage Boundary Wall Structure	Anecdotal reports of potential previous blockage at the boundary wall occurring and exacerbating flooding upstream to the rear of the main street properties.
3	Arrigle Business Park Culvert	Anecdotal reports of previous blockage at the culvert. Culvert is built over and so flows may get 'trapped' on upstream face creating large increases in flood levels upstream.
4	Main Street Bridge	Local reports that the structure is prone to siltation build up and has previously had sedimentation on the upstream face removed.
5	Ballyhale Tributary	The Ballyhale tributary runs adjacent to the school, it has been reported the channel is prone to block. Site observations indicate densely vegetated banks downstream of the '90 degree bend', likely to promote blockage. Overland flow from the watercourse would tend to the main street via the laneway at 'Sheff's pub', correlating with observed flooding.

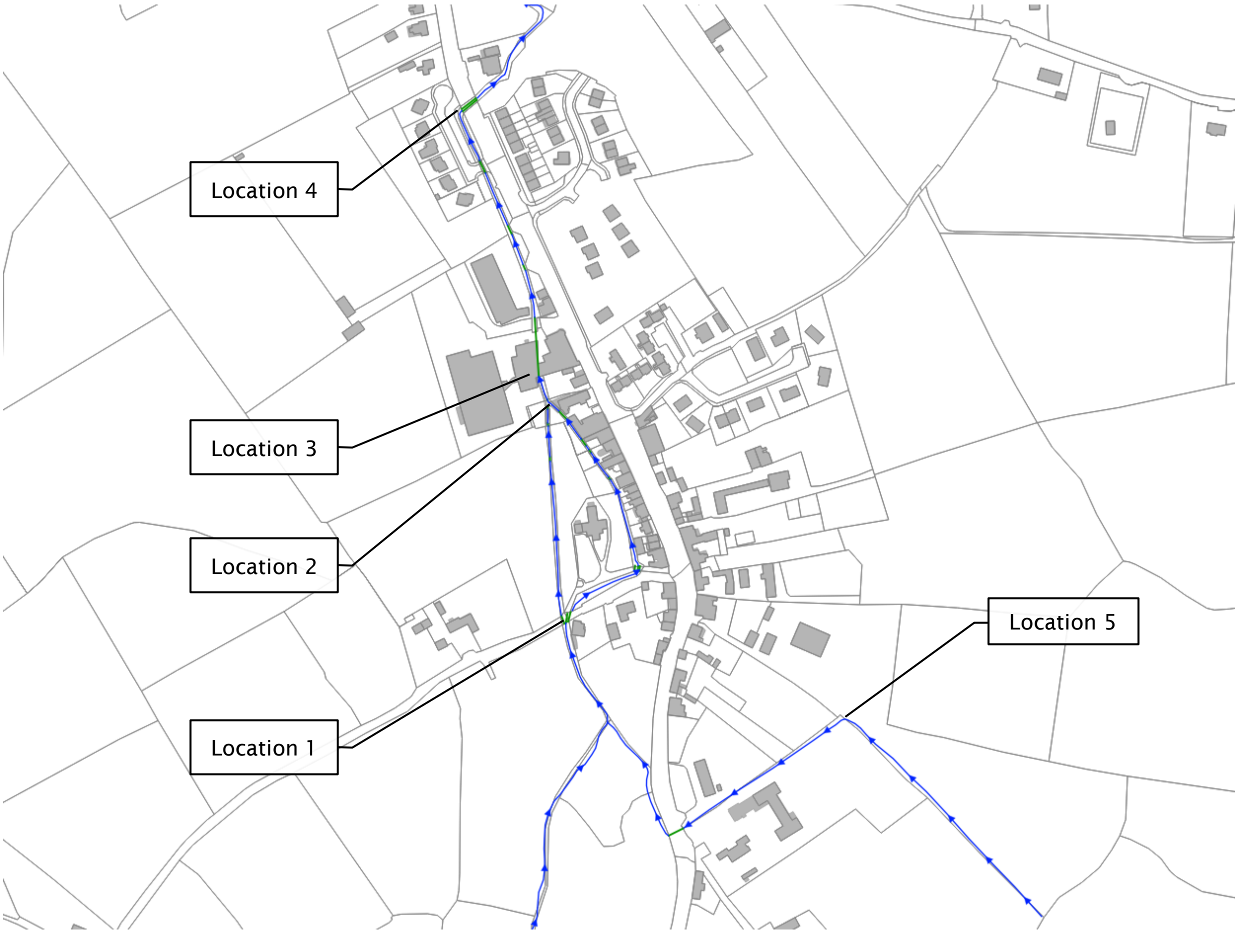


Figure 5-5 Blockage Locations

5.6 Artificial Sources

Review of Prime2 mapping and orthophotography indicated no reservoir, canal or other potentially impounded lakes upgradient of Ballyhale that would have potential to cause a risk of flooding in the event of a breach or other failure, or have an attenuating effect on flood hydrology.

5.7 Summary

Flood risk in Ballyhale historically appears to have been mainly influenced by fluvial flooding (including the likely effect of culvert blockages).

Analysis of the sources of flooding found no significant groundwater, pluvial, urban drainage or artificial factors affecting fluvial hydrology or flow rates for hydraulic modelling purposes.

Considering this and our assessment of the historic flooding records and catchment characteristics it is concluded that a catchment-based fluvial estimation approach is deemed the most appropriate approach for estimation of fluvial flood risk for the Study Area.

Local surface water overland flows along the main street identified by this assessment and from anecdotal historic reports have been investigated and concluded to originate as out of bank flows from an upstream unmapped tributary of the Ballyhale River and so is most appropriately assessed by fluvial hydrology with the tributary included as part of the fluvial hydraulic model.

6 HYDROLOGICAL ESTIMATION POINTS

6.1 HEP Selection

Hydrological Estimation Points (HEPs) selected for estimation of flows within the model are shown in the following Figure 6-1 and detailed in Table 6-1. The model extent is as described previously in section 2.2.

HEPs have been adopted based on the following criteria:

- Upstream boundaries of all major watercourses,
- Points on tributaries upstream of the confluence with the receiving channel,
- Points on receiving channels upstream/downstream of confluences of tributaries,
- Potential watercourse diversions / optioneering points (based on the CFRAM option envelope) to accurately represent flows in areas of greatest interest.
- Ensure a maximum 2km HEP interval along the modelled reach.

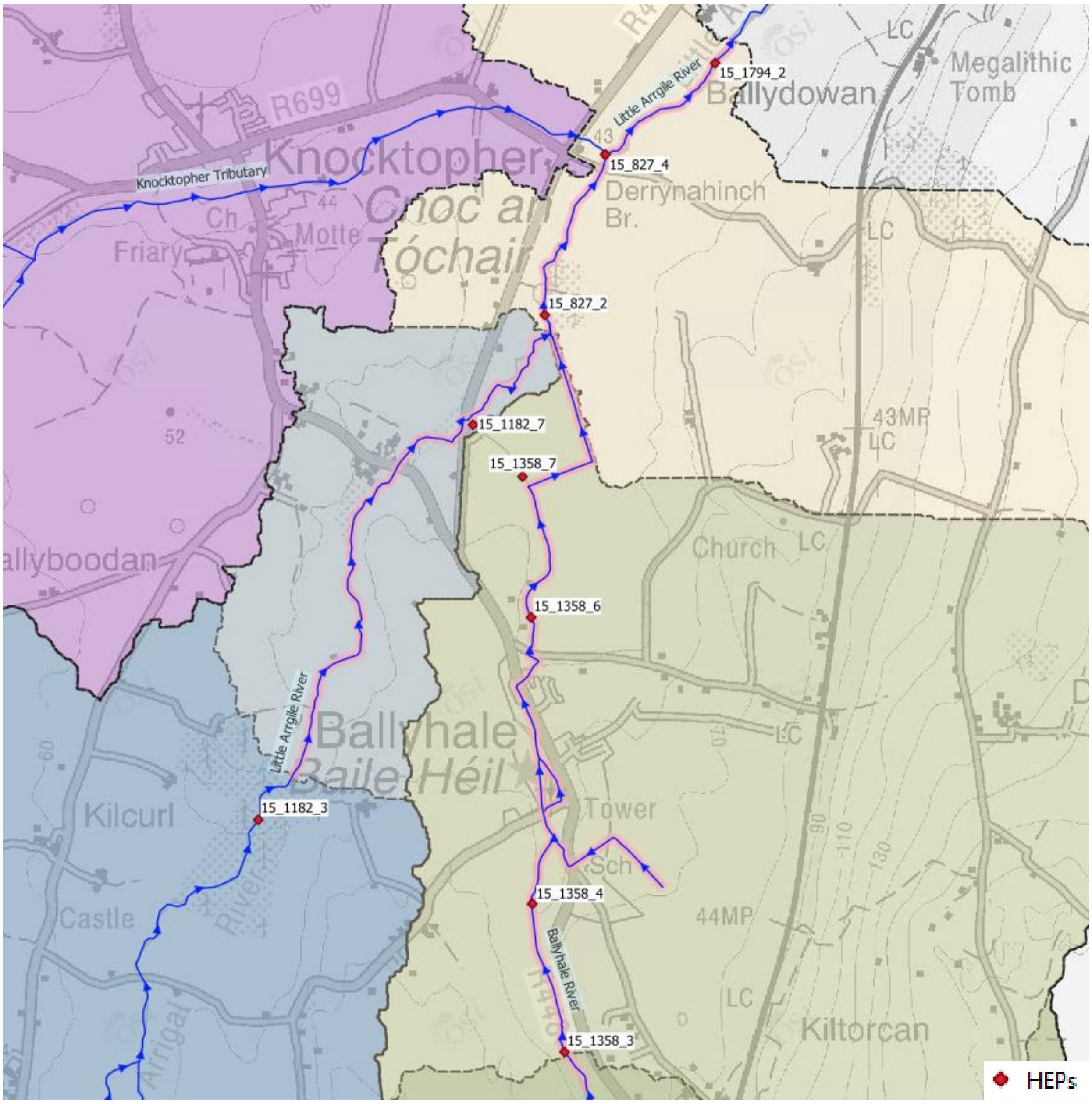


Figure 6-1 Hydrological Estimation Points

Table 6-1 Study HEPs

HEP	Purpose	Intended Application of Flows to the Model
15_1358_3	U/S extent of Ballyhale River.	Point inflow at upstream limit of modelled reach.
15_1358_4	Confluence U/S between Ballyhale River and Ballyhale Tributary on Ballyhale River.	Top up flows to be applied as a lateral inflow to Ballyhale River between 15_1358_3 and 15_1358_4.
15_1358_6	D/S of Ballyhale Village.	Top up flows to be applied as a lateral inflow to Ballyhale River between 15_1358_4 and 15_1358_6.
15_1182_3	U/S extent of Little Arrigle River.	Point inflow at upstream limit of modelled reach.
15_1182_7	Confluence U/S between Little Arrigle and Ballyhale Rivers on Little Arrigle.	Top up flows to be applied as a lateral inflow to Little Arrigle between 15_1882_3 and 15_1182_7.
15_1358_7	Confluence U/S between Little Arrigle and Ballyhale Rivers on Ballyhale.	Top up flow to be applied as a lateral inflow to Ballyhale River between 15_1358_6 and 15_1358_7.
15_1212_7	Represent Knocktopher tributary flows to Little Arrigle.	Point inflow on confluence with Little Arrigle River.
15_827_4	Confluence U/S of Knocktopher tributary and Little Arrigle on Little Arrigle.	Top up flows to be applied as lateral inflow on the Little Arrigle between 15_827_2 and 15_827_4.
15_1794_2	D/S extent of Little Arrigle River reach to be modelled.	Top up flow to be applied as lateral inflow on the Little Arrigle between 15_1212_7 and 15_1794_2.

The Ballyhale Tributary is not mapped on the FSU portal, no corresponding HEP is therefore available. Flows to be calculated pro-rata from the main Ballyhale River catchment.

HEPs shall be used within the flood model to check and ensure flows are consistent with modelled flows, any instances where significant differences occur shall be investigated, remedied or reported on where there is suitable justification for difference provided.

6.2 HEP Characteristics

HEP physical characteristics derived from the FSU portal are detailed in the following table. Characteristics have been verified where possible using available GIS datasets. It is noted that many of the datasets remain unchanged from their use in FSU.

Table 6-2 HEP Physical Characteristics

HEP	Catchment (km²)	BFISOIL	SAAR (mm)	FARL	DRAIND (km/ km²)	S1085 (m/km)	ARTDRAIN2	URBEXT
15_1358_3	10.328	0.646	1036.98	1	0.237	12.6643	0	0
15_1358_4	10.836	0.6465	1036.33	1	0.272	13.021	0	0
15_1358_6	11.834	0.6475	1034.79	1	0.333	12.1061	0	0
15_1182_3	10.162	0.6593	1033.63	1	0.168	3.851	0	0
15_1182_7	13.094	0.6602	1029.66	1	0.26	2.712	0	0
15_1358_7	11.964	0.6477	1034.6	1	0.391	11.0137	0	0
15_1212_7	15.092	0.7056	995.9	1	0.386	4.7529	0	0
15_827_4	28.422	0.6413	1030.33	1	0.324	9.1836	0	0
15_1794_2	44.923	0.6551	1018.32	1	0.346	8.3273	0	0
% Difference (Max v Min)		9%	4%	0%	57%	79%	0%	0%

Catchment characteristics largely correlate for each HEP considered. DRAIND (drainage density) and S1085 (mainstream slope) have a higher degree of variance between upstream and downstream HEPs.

Catchment areas have been updated from catchment analysis conducted with best available height data. Verification of the Standard Annual Average Rainfall (SAAR) was conducted using Met Eireann datasets. Data from the two closest weather stations to Ballyhale village was analysed and is detailed in the following table, indicating a SAAR of 922-1134mm, within the range presented in Table 6-2.

Table 6-3 SAAR Analysis

Station	Data Years	Station Elevation	Proximity to Model Area	Annual Rainfall		
				Minimum	Average	Maximum
Thomastown (Mt. Juliet)	1991-2014	49m	4km to north	734	922	1155
Mullinavat (Glendonnell)	1985-2019	94m	11km to south	869	1134	1550

7 INDEX FLOOD ESTIMATION

7.1 Preamble

Determination of the design flood relies on estimation of an index flood (Qmed) (median annual flood discharge) and application of a flood growth factor estimated from a flood frequency curve for the T-year return period of the flood of interest.

The wider hydrological estimation approach adopted in this assessment seeks to estimate appropriate index floods at each HEP. It is then intended to adopt a single regional flood frequency curve to determine growth factors. Adoption of a single FFC is an acceptable rationalisation given the broad similarly in HEPs under consideration as indicated in Table 6-2, and the lack of additional value in undertaking HEP-specific FFC analysis where the pooling group is likely to return identical sites due to the limited number of contributing stations.

This report section discusses the selection of appropriate index flood estimates.

7.2 Flood Estimation Methods

OPW guidance is that FSU methodology is the most robust and widely accepted flow estimation hydrology commonly used within Ireland and accepted within the industry. However, due to underrepresentation of smaller catchments within the pooling data OPW FSU team recommends that those methods should be used with caution for all catchments < $25km^2$, and therefore should be compared against other flow estimation methods (hereafter termed "legacy methods").

Guidance is not explicit in requiring use of legacy methods where they indicate a more conservative estimate than FSU-based methods. In the instance where legacy methods provide a more conservative estimate the model will be stress tested to assess the impact on results.

The FSU methodology has a lower factorial standard error (1.37) than other methods and therefore is the preferred method of choice based on professional experience.

7.2.1 CFRAM Validation

Whilst this project is independent from the CFRAM study, it is prudent to assess against CFRAM due to the extensive validatory work that was incorporated in the CFRAM work packages. CFRAM hydrology (catchment extents and catchment descriptors) has been described and validated in Section 3 and 4.

To enable a direct comparison with the CFRAM study, the following key HEPs where this project and the CFRAM overlap are initially considered:

- HEP 1 – 15_1814_4 – U/S of River Nore
- HEP 2 – 15_1212_7 – Knocktopher Tributary
- HEP 3 – 15_1182_7 – Little Arrigle River at Ballyhale Confluence
- HEP 4 – 15_1358_3 – Ballyhale River U/S of Ballyhale Village

Key HEP catchments along with pivotal sites considered are shown in the following Figure 7-1.

7.2.2 Approach to the Assessment

The approach taken by this project has been to assess index floods based on the FSU 7 variable method in the first instance with gauged-data transfer based on pivot sites in the following hierarchy:

i. Most Hydrologically Similar Pivot – Station 13002
ii. Downstream Gauge Pivot – Station 15006
iii. Geographically Closest (Centroid) Pivot -Station 15001

The most appropriate pivotal donor is assessed based on professional judgement. Reassurance / sensibility checking and future sensitivity testing is informed by estimates derived from:

- FSU 5 Variable Equation[5],

[5] Gebre, F; Nicholson, O. (2012). Flood Estimation in Small and Urbanised Catchments in Ireland. Trim, Co. Meath: OPW.

- Flood Studies Supplementary Report[6] No. 6 3-variable equation,
- Flood Studies Report[7] method 6 variable equation, and
- Institute of Hydrology Report 124 – Flood Estimation in Small Catchments (IH124)[8]

The initial approach was tested on the 4 key HEPs, with the preferred approach subsequently adopted to the remaining 5 HEP locations.

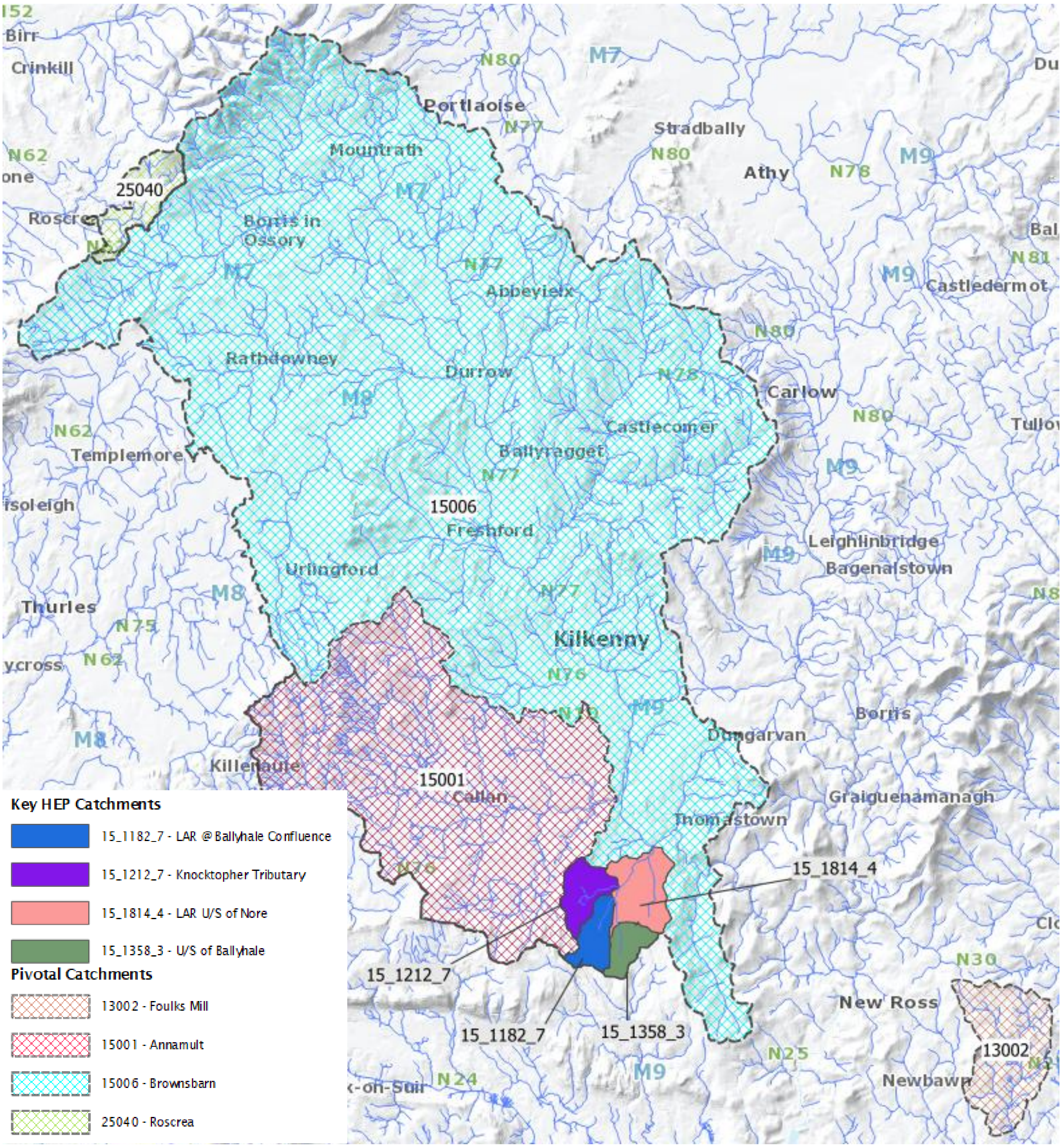


Figure 7-1 Key HEP and Pivotal Catchments

[6] NERC, (1985). The FSR rainfall-runoff model parameter estimation equations updated, Flood Studies Supplementary Report (FSSR), National Environmental Research Council, London.
[7] NERC, (1975). Flood Studies Report, National Environmental Research Council, London.
[8] Institute of Hydrology. (1994). Report No. 124, Flood Estimation for Small Catchments.

7.3 Key HEP Index Flood Estimates

7.3.1 Index Flood Estimates

7.3.1.1 HEP 1 – 15_1814_4 – Upstream of River Nore

Pivotal sites for FSU index flood estimation update in accordance with the FSU hierarchy are as follows:

1. Downstream Gauging Station -15006 Brownsbarn
2. Geographically Closest (Centroid) – 15001 Annamult
3. Most Hydraulically Similar Pivot – 13002 Foulks Mill

Refer to Table 6-2 for catchment properties for the HEP. As the catchment is <25km^2 it was necessary to assess the FSU derived flows against flows derived from FSR / FSSR and IoH methodologies. A summary of flows calculated as part of this study and the index flow adopted for the CFRAM study are detailed in the following table.

Table 7-1 Index Flood Comparison – HEP 15_1814_4

HEP1 - REF 15_1814_4 (U/S of Nore)	QMED (m^3/s)	%-Difference (CFRAM)	%-Difference (Max Estimate)
CFRAM Study Calculated QMED	**10.09**	**0%**	-40%
FSU QMED - Most Hydrologically Similar Pivot - 13002	8.36	-17%	-50%
FSU QMED - D/S Gauge Pivot - 15006	10.74	6%	-36%
FSU QMED - Geographically Closest (Centroid) Pivot -15001	9.89	-2%	-41%
FSU QMED - 7 Variable	7.71	-24%	-54%
FSU QMED – 5 Variable	16.80	67%	**0%**
FSSR (3 Variable) - Q2 - Ireland	11.48	14%	-32%
FSR (6 Variable) - Q2 - Ireland	10.95	9%	-35%
IoH124 - Q2 - Ireland	9.56	-5%	-43%

[1]In order to make a direct comparison to QMED, the legacy method flows (FSR, FSSR, and IoH124) have been scaled by from QBAR to QMED using GDSDS growth curves, adopted as most applicable to the site (versus old Irish growth curves).

7.3.1.2 HEP 2 – 15_1212_7 – Knocktopher Tributary

Three pivotal sites were assessed in accordance to the FSU hierarchy and include:

1. Downstream Gauging Station -15006 Brownsbarn
2. Geographically Closest (Centroid) – 15001 Annamult
3. Most Hydraulically Similar Pivot – 13002 Foulks Mill

Refer to Table 6-2 for catchment properties for the HEP. As the catchment is <25km^2 it was necessary to assess the FSU derived flows against flows derived from FSR / FSSR and IoH methodologies. A summary of flows calculated as part of this study and the index flow adopted for the CFRAM study are detailed in the following table.

Table 7-2 Index Flood Comparison – HEP 15_1212_7

HEP2 - REF 15_1212_7 (Knocktopher Tributary)	QMED (m3/s)	%-Difference (CFRAM)	%-Difference (Max Estimate)
CFRAM Study Calculated QMED	**2.24**	**0%**	-41%
FSU QMED - Most Hydrologically Similar Pivot - 13002	2.3	3%	-40%
FSU QMED - D/S Gauge Pivot - 15006	2.4	7%	-37%
FSU QMED - Geographically Closest (Centroid) Pivot -15001	2.21	-1%	-42%
FSU QMED - 7 Variable	1.72	-23%	-55%
FSU QMED – 5 Variable	3.80	70%	**0%**
FSSR - Q2 - Ireland	3.02	35%	-21%
FSR - Q2 - Ireland	2.47	10%	-35%
IoH124 - Q2 - Ireland	2.63	14%	-31%

[1]In order to make a direct comparison to QMED, the legacy method flows (FSR, FSSR, and IoH124) have been scaled by from QBAR to QMED using GDSDS growth curves, adopted as most applicable to the site (versus old Irish growth curves).

7.3.1.3 HEP 3 – 15_1182_7 – Little Arrigle River at Ballyhale Confluence

Three pivotal sites were assessed in accordance to the FSU hierarchy and include:

1. Downstream Gauging Station -15006 Brownsbarn
2. Geographically Closest (Centroid) – 15001 Annamult
3. Most Hydraulically Similar Pivot – 25040 Roscrea

Refer to Table 6-2 for catchment properties for the HEP. As the catchment is <25km^2 it was necessary to assess the FSU derived flows against flows derived from FSR / FSSR and IoH methodologies. A summary of flows calculated as part of this study and the index flow adopted for the CFRAM study are detailed in the following table.

Table 7-3 Index Flood Comparison – HEP 15_1182_7

HEP3 - REF 15_1182_7 (LAR @ Ballyhale)	QMED (m^3/s)	%-Difference (CFRAM)	%-Difference (Max Estimate)
CFRAM Study Calculated QMED	**1.72**	**0%**	-46%
FSU QMED - Most Hydrologically Similar Pivot - 25040	0.74	-57%	-77%
FSU QMED - D/S Gauge Pivot - 15006	1.84	7%	-43%
FSU QMED - Geographically Closest (Centroid) Pivot -15001	1.69	-2%	-47%
FSU QMED - 7 Variable	1.32	-23%	-59%
FSU QMED – 5 Variable	3.21	87%	**0%**
FSSR - Q2 - Ireland	2.76	60%	-14%
FSR - Q2 - Ireland	1.78	3%	-45%
IoH124 - Q2 - Ireland	2.41	40%	-25%

[1]In order to make a direct comparison to QMED the legacy method flows (FSR, FSSR, and IoH124) have been scaled by from QBAR to QMED using GDSDS growth curves, adopted as most applicable to the site (versus old Irish growth curves).

7.3.1.4 HEP 4 – 15_1358_3 – Ballyhale River Upstream of Ballyhale Village

Three pivotal sites were assessed in accordance to the FSU hierarchy and include:

1. Downstream Gauging Station -15006 Brownsbarn
2. Geographically Closest (Centroid) – 15001 Annamult
3. Most Hydraulically Similar Pivot – 25040 Roscrea

Refer to Table 6-2 for catchment properties for the HEP. As the catchment is <25km² it was necessary to assess the FSU derived flows against flows derived from FSR / FSSR and IoH methodologies. A summary of flows calculated as part of this study and the index flow adopted for the CFRAM study are detailed in the following table.

Table 7-4 Index Flood Comparison – HEP 15_1358_3

HEP3 - REF 15_1358_3 (U/S of Ballyhale)	QMED (m^3/s)	%-Difference (CFRAM)	%-Difference (Max Estimate)
CFRAM Study Calculated QMED	**1.9**	**0%**	-51%
FSU QMED - Most Hydrologically Similar Pivot - 25040	0.78	-59%	-80%
FSU QMED - D/S Gauge Pivot - 15006	1.95	3%	-50%
FSU QMED - Geographically Closest (Centroid) Pivot -15001	1.8	-5%	-54%
FSU QMED - 7 Variable	1.4023	-26%	-64%
FSU QMED – 5 Variable	3.904	106%	**0%**
FSSR - Q2 - Ireland (GDSDS Growth Curves)	2.33	23%	-40%
FSR - Q2 - Ireland	1.95	3%	-50%
IoH124 - Q2 - Ireland	2.05	8%	-48%

[1]In order to make a direct comparison to QMED, the legacy method flows (FSR, FSSR, and IoH124) have been scaled by from QBAR to QMED using GDSDS growth curves, adopted as most applicable to the site (versus old Irish growth curves).

7.3.2 Factorial Standard Error

The uncertainty associated with the estimation of QMED can be measured in terms of an upper (95%) and lower (68%) confidence range, calculated using the Factorial Standard Error (FSE) stated for hydrological analysis method. Methodologies with a lower FSE provide a lower variance in upper and lower confidence bounds and therefore higher confidence in the result.

The 68% confidence lower and upper bounds are in the range QMED/1.37 – QMED*1.37, whereas the 95% confidence lower and upper bounds are in the range QMED/$1,37^2$ – QMED*1.37^2.

The FSE associated with 7 variable QMED estimation using FSU is 1.37 (versus 1.46 for the FSR method and 1.64 for IoH124). The FSE associated with the FSU 5 variable equation was calculated by Gebre and Nicholson[9] as 1.674, however this was only using a relatively small study group of 38 catchments under than 30km².

The confidence levels are useful to gauge if the pivotal adjusted flow is likely to be an over or underestimation. The pivotal adjusted QMEDs for the key HEPs and respective 68% and 95% confidence limits are detailed on the following Table 7-5.

[9] Gebre, F; Nicholson, O. (2012). Flood Estimation in Small and Urbanised Catchments in Ireland. Trim, Co. Meath: OPW.

The downstream gauge (15006 Brownsbarn) pivotal site tends to exceed the 68% upper confident limit for all HEPs, indicating that it may be overestimating flows. The geographically closest pivot (15001 – Annamult) lies within both 68% and 95% confidence ranges in all instances.

Table 7-5 HEP Factorial Standard Error Confidence Limits

HEP	Pivot	Qmed (unadjusted)	Qmed (adjusted)	68% Lower	68% Upper	95% Lower	95% Upper
15_1814_4	15006	7.71	10.74	5.63	10.56	4.11	14.47
	15001		9.89	5.63	10.56	4.11	14.47
	13002		8.36	5.63	10.56	4.11	14.47
15_1212_7	15006	1.72	2.40	1.26	2.36	0.92	3.24
	15001		2.21	1.26	2.36	0.92	3.24
	13002		2.30	1.26	2.36	0.92	3.23
15_1182_7	15006	1.32	1.84	0.96	1.81	0.70	2.48
	15001		1.69	0.96	1.81	0.70	2.48
	25040		0.74	0.96	1.81	0.70	2.48
15_1358_3	15006	1.40	1.95	1.02	1.92	0.75	2.63
	15001		1.80	1.02	1.92	0.75	2.63
	25040		0.78	1.02	1.92	0.75	2.63

7.3.3 Analysis

As discussed in Section 3, the FSU portal only includes water year data up until 2004. A review of EPA HydroNet hydrometric data was carried out for the gauged pivotal sites used to determine the effect of the additional 14 years of available water years data on the HydroNet portal not updated to the FSU portal.

Inclusion of additional water years data has the potential effect of increasing / decreasing the likelihood of a storm event if the missing data period covered particularly 'dry' or 'flood rich' periods i.e. an increase in average AMAX indicates the additional data years were 'flood rich' and so the growth factors for higher return periods are increased.

The difference in average AMAX for the records of data up to 2004 and up to 2018 is detailed in the following table indicating that for the Annamult gauging site taken as the pivotal site for all HEPs had an increase in the median AMAX by 5%. The Brownsbarn and Roscrea pivotal sites had an increase in median AMAX of 5% and 8.6% respectively whereas Foulks Mill resulted a median decrease of 4.3%.

Table 7-6 AMAX Difference between 2004 and 2018 Datasets

	15001 Annamult	15006 Brownsbarn	25040 Roscrea	13002 Foulks Mill
Average	1.6%	0.7%	8.9%	-3.8%
Median	5.0%	5.0%	8.6%	-4.3%

The additional water years indicates a median increase of 5% in AMAX series, indicating the index flows calculated are potentially underestimated.

The analysis outlined above was undertaken to provide an indicator of how likely the FSU data would be influenced by the additional water years only. The high-level review of water year data suggested that AMAX values were not significantly affected across the range of sites considered. A full review of all gauging data is disproportionate to the size and scale of this ungauged catchment analysis due to the inbuilt margin of error. Based on previous professional experience, the FSU portal AMAX values are not considered sufficiently disparate to undertake a site-specific re-build and application of processes used by the FSU portal. The hydraulic modelling exercise and testing of options will include analysis of sensitivity of the scheme to potential for underestimation of flows, to ensure that potential variation is captured with freeboard.

Key findings are as follows:

- Calculation of QMED by the 7 variable equation provided an underestimate in the range of 52-33% versus all other methodologies and 26-23% versus the QMED adopted as part of the CFRAM study.
- All pivotal site data transfers tend to increase the estimation of Qmed. The suggested hierarchy in selecting pivotal sites within FSU would give preference in opting for a pivotal site at a downstream gauging point. For all instances considered, the downstream pivotal catchment is unsatisfactorily dissimilar in Euclidian characteristics (particularly catchment area), tending to be above the 68% confidence upper limit and as such is discounted in favour of the most geographically similar pivot which proves more similar in Euclidean characteristics and lays within both 68% and 98% confidence ranges.
- The preferred method arising from the analysis of key HEPs is that use of the FSU analysis with geographically similar pivot offers the most appropriate outcome. As such the remaining 5 HEP index floods are similarly calculated by way of this methodology.
- In all instances the FSU 5 variable equation provided the largest magnitude estimate, between 40% - 51% larger than estimates derived as part of the CFRAM study. Whilst the 5 variable equation results believed to be more suited to smaller catchments it was acknowledged that the study was based on a relatively small number (38) of catchments within Ireland and recommends the FSU 7-variable equation is preferred for all catchments with an area greater than $5km^2$.
- The chosen FSU 7-variable methodology (geographically closest pivotal adjustment) estimate correlates well with the CFRAM Qmed estimate.

7.3.4 Adopted Index Flow

The assessment has concluded that the FSU method remains the preferred method for all HEPs considered. The geographically closest (Centroid) pivot (15001 Annamult) estimate is deemed appropriate for use.

Comparison with the FSU 5-variable estimates indicates that the 5 variable estimates indicate a significant overestimation in comparison to all other methodologies. The 5-variable equation methodology is in its infancy and has not be subject to rigorous testing, the study also noted greatly varying QMED values may occur dependant on where the gauging point was taken. Use of the 5 variable equation is deemed not appropriate for use in this instance.

Comparison with legacy method estimates indicates that FSU methods tend to offer similar or lower estimates. The absolute variance in estimates is insufficiently large to justify deviating away from FSU methods, and potential for underestimation will be investigated through sensitivity testing in the hydraulic model.

7.4 Summary of Index Flood Estimates

Model index flows were calculated using the FSU portal and are detailed in Table 7-7. Flows were scaled by an areal adjustment factor to represent the updated catchment areas calculated using best available height data.

Table 7-7 Model Index Flows

HEP	Location	Application	Areal Adjustment Factor	Scaled QMED (m^3/s)
15_1358_3	U/S extent of Ballyhale River.	Point inflow at upstream limit of modelled reach.	0.929	1.67
15_1358_4	Confluence U/S between Ballyhale River and Ballyhale Tributary on Ballyhale River.	Top up flows to be applied as a lateral inflow to Ballyhale River between U/S extent of model and bifurcation at church.	0.916	1.81
15_1358_6	D/S of Ballyhale Village	Top up flows to be applied as a lateral inflow to Ballyhale River between 15_1358_4 and 15_1358_6.	0.982	2.22
15_1182_3	U/S extent of Little Arrigle River.	Point inflow at upstream limit of modelled reach.	1.117	1.38
15_1182_7	Confluence U/S between Little Arrigle and Ballyhale Rivers on Little Arrigle.	Top up flows to be applied as a lateral inflow to Little Arrigle between 15_1882_3 and 15_1182_7.	0.923	1.56
15_1358_7	Confluence U/S between Little Arrigle and Ballyhale Rivers on Ballyhale.	Top up flow to be applied as a lateral inflow to Ballyhale River between 15_1358_6 and 15_1358_7.	1.182	2.80
15_1212_7	Represent Knocktopher tributary flows to Little Arrigle.	Point inflow on confluence with Little Arrigle River.	1.119	2.47
15_827_4	Confluence U/S of Knocktopher tributary and Little Arrigle on Little Arrigle.	Top up flows to be applied as lateral inflow on the Little Arrigle between 15_827_2 and 15_827_4	0.971	4.72
15_1794_2	D/S extent of Little Arrigle River reach to be modelled.	Top up flow to be applied as lateral inflow on the Little Arrigle between 15_1212_7 and 15_1794_2.	1.052	7.61

8 GROWTH CURVE ESTIMATION

8.1 Preamble

Growth factors are required to apply to the estimated index flood to obtain the T-year flood magnitude.

Estimation of index floods has indicated that the preferred method remains FSU-based methods and as such further consideration of FSR/legacy based national growth curves is excluded from further consideration.

The following analysis seeks to estimate growth factors based on FSU statistical methods with reference to CFRAM methods.

8.2 FSU Growth Factor Estimation

Water year data available for pooling on the FSU portal is for the years up to 2004 only. It has been established that as part of the CFRAM study, additional pooling data up to 2009 was added for analysis within the study by the consultants as part of the wider South Eastern study.

8.2.1 FSU Portal Analysis

Due to the influence of regional characteristics and required length of water years which would tend to "dilute" a pooling group particularly in instances where the group of small donor catchments is limited, an initial exercise was undertaken to explore and stress test pooling outcomes as follows:

- Recommended method – i.e. 5xTyr (500 yr. record length)
- Regional pooling group – i.e. geographic similarity (90 yr. record length)
- Euclidian similarity group – i.e. to limit the group to small catchments (50 yr. record length).

Flood growth curves for these scenarios are indicated on the following Figure 4.3. It is immediately apparent that all methodologies represent a significant underestimate versus previous CFRAM analyses.

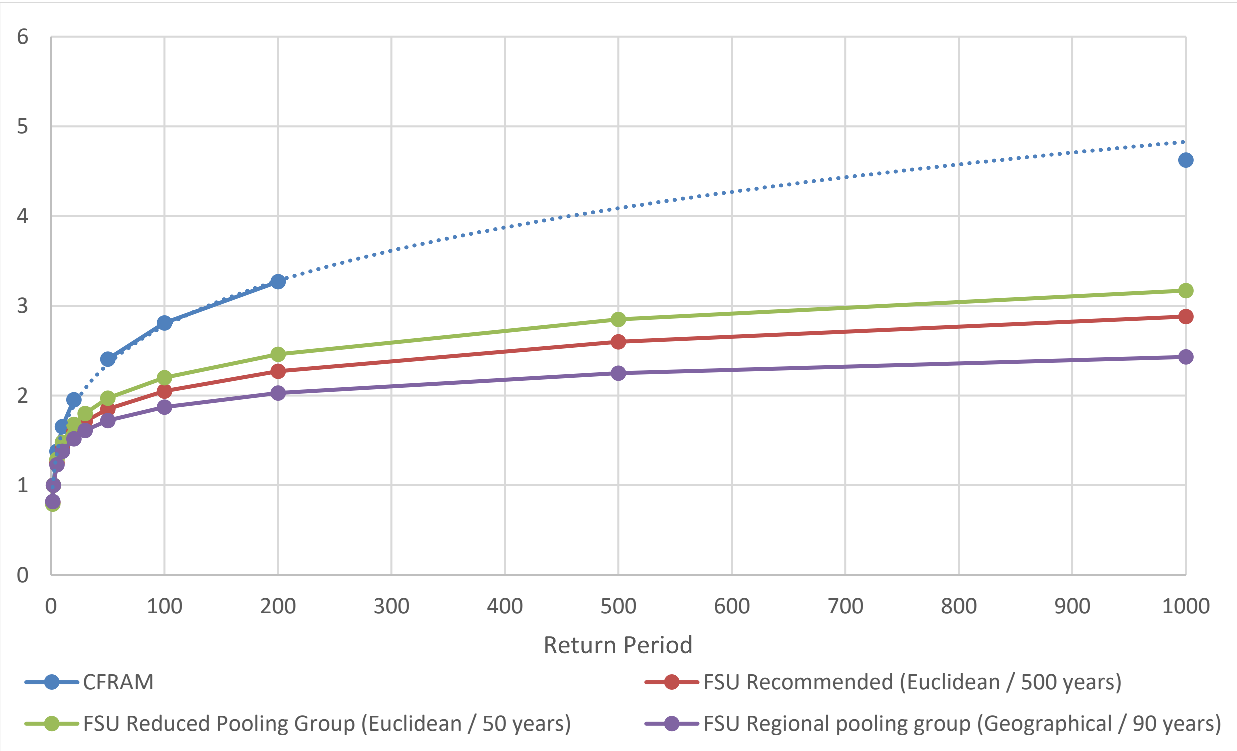


Figure 8-1 CFRAM - FSU Growth Curve Comparison (HEP 15_1358_3, Pivotal Station: 15001 Annamult, Distribution: GLO)

8.2.2 Effect of Additional Water Years

As noted previously, CFRAM analysis included assessment of water years beyond that contained within the FSU portal. The CFRAM consultant records that a review was carried out of EPA gauged data which indicated that the period following 2004 was 'flood rich'. CFRAM growth curves were calculated on a site specific basis for HEPs considered.

This assessment has sought to qualify the continued appropriateness of utilising either the FSU portal growth curve (utilising water years to 2004) and/or the CFRAM growth curve (utilising water years to 2009).

A sample set of pooling group donor sites were identified that were significant to any pooling analysis at Ballyhale by way of their Euclidian and geographical similarity, detailed below:

- 25040 Roscrea (15_1358_3 rank 1; 15_1814_4 rank 4)
- 25034 Rochfort (15_1358_3 rank 2)
- 25027 Gourdeen (15_1814_4 rank 1)
- 13002 Folks Mill (15_1814_4 rank 2)
- 26010 Riverstown (15_1814_4 rank 4)
- 15001 Annamult (Geographically closest pivotal site)
- 15006 Brownsbarn (Downstream gauge)

The review comprised:

AMAX review

An AMAX series was derived from EPA logged datasets. It was noted that where the FSU portal record overlaps with the EPA series there are discrepancies between the absolute gauged value for the EPA dataset and the AMAX noted within the FSU dataset. It is undetermined at this juncture the rationale behind this, however it is probable that some floods may have been disregarded or downgraded following a detailed OPW review in forming the FSU dataset, or due to undocumented changes in the flood rating curve at individual sites.

QMED update

By accepting published gauged data on the EPA portal (ignoring discrepancies), analysis by a simple comparison of median AMAX as a measure of the likelihood of change in the growth curve indicates that from a sample site at Annamult the additional water years 2005-2009 (assessed by RPS at CFRAM) causes an increase in median AMAX of circa +5.5% from the FSU dataset.

Assessing the median AMAX to include the additional period up to 2018 would causes a similar or slightly reduced QMED to CFRAM study. Table 8-1 details a brief review of other statistically similar stations with high rankings in respective pooling groups which indicates that inclusion of 2009-19 AMAX would cause similar or increased QMED estimates.

Station 25040 (Roscrea) indicates an increase of 7.7% in AMAX median between CFRAM and 2018 data, a sensitivity analysis to the model to flow magnitude will be conducted to assess the significance of flow uncertainty to the scheme.

Table 8-1 Median AMAX Update

Data	15001 Annamult	15006 Brownsbarn	25040 Roscrea	13002 Foulks Mill
Up to 2004 (FSU Portal)	84.13	289.14	3.80	9.62
Up to 2009 (CFRAM) (Difference to 2004)	88.73 (+5.5%)	303.59 (+5%)	3.83 (+0.8%)	9.03 (-6.2%)
Up to 2018 (Difference to CFRAM)	88.31 (-0.5%)	303.59 (+0%)	4.13 (+7.7%)	9.21 (2%)

It is concluded that inclusion of the 2004-2009 water years at CFRAM has generally captured the most significantly flood rich period and that additional water years are unlikely to significantly distort the dataset.

It is noted that the FSU portal is unable to be modified by external consultants to add additional pooling data / water years and no readily available method for updating pooling data is available for the purpose of this study without a significant work package.

Spreadsheets used as a pre-cursor to the FSU portal were used by the CFRAM consultants when calculating their updated growth curve using additional water years. The FSU spreadsheets were not made available for the purpose of this study, therefore no verified / readily accessible method of updating the FSU pooling data with additional water years was able to be performed within the study timescales.

8.2.2.1 Summary

Additional water years subsequent to 2004 are likely to cause donor flood growth curves derived from the FSU dataset to be insufficiently low and as such it is not recommended to base growth curves on the limited FSU-pooling data.

It is therefore proposed to adopt the growth curves determined as part of the CFRAM study which provide an additional 5 years of pooling data to determine the design flows. It has been determined that the additional water years since the CFRAM study are unlikely to significantly vary the outcome if subject to a new analysis.

The adopted set of growth curves carry the highest degree of certainty at the site and provide the most conservative estimate of flows while consistent with other estimates, therefore there is confidence in their usage.

It has been verified that the RPS growth curves are appropriate in terms of capturing a flood rich period that renders the FSU dataset an underestimate for this specific site.

Table 8-2 Adopted Growth Curves

Return Period	15_1814_4 (U/S of Nore)	15_1212_7 (Knocktopher Tributary)	15_1182_7 (Little Arrigle at Ballyhale)	15_1358_3 (U/S of Ballyhale)
t=2	1	1	1	1
t=5	1.30	1.44	1.37	1.38
t=10	1.50	1.76	1.65	1.65
t=20	1.71	2.13	1.94	1.95
t=50	2.02	2.69	2.38	2.41
t=100	2.28	3.20	2.77	2.81
t=200	2.56	3.79	3.22	3.27
t=1000	3.34	5.59	4.53	4.63

Potential for the growth curves to be an underestimate can be evaluated by stress testing within the model for the proposed scheme, with potentially uncertainty mitigated by robust freeboard to any scheme.

8.3 HEP Growth Curves

Rationale for growth curve application to the expanded HEP set is detailed in the following table.

Table 8-3 HEP Growth Curve Rationale

HEP	Growth Curve	Rationale
15_1358_3	15_1358_3	HEP situated on USL of the Ballyhale River; growth curve used calculated as part of the CFRAM study at this location.
15_1358_4	15_1358_3	HEP situated along the Ballyhale River; growth curve based on upstream reach of Ballyhale River deemed to be most representative.
15_1358_6	15_1358_3	HEP situated along the Ballyhale River; growth curve based on upstream reach of Ballyhale River deemed to be most representative.
15_1182_3	15_1182_7	HEP situated on the USL of the Little Arrigle River; growth curve based on the Little Arrigle at its confluence with the Ballyhale River deemed to be most representative.
15_1182_7	15_1182_7	HEP situated on the Little Arrigle River at its confluence with the Ballyhale River; growth curve used calculated as part of the CFRAM study at this location.
15_1358_7	15_1358_3	HEP situated on the Ballyhale River U/S of the Little Arrigle confluence; growth curve based on upstream reach of Ballyhale River deemed to be most representative.
15_1212_7	15_1212_7	HEP represents flows from the Knocktopher Tributary to the Little Arrigle River; growth curve used calculated as part of the CFRAM study at this location.
15_827_4	15_1814_4	HEP represents flows on the Little Arrigle River U/S of the Knocktopher confluence; growth curve based on the Little Arrigle River U/S of the River Nore confluence deemed to be most representative.
15_1794_2	15_1814_4	HEP represents DSL of the intended model reach on the Little Arrigle River; growth curve based on the Little Arrigle River U/S of the River Nore confluence deemed to be most representative.

9 MODEL INPUT

9.1 Model Flows

A summary of design flood discharge for T-year floods for present-day, mid-range future and high-end future scenarios are scheduled in the following tables.

Mid-Range Future Scenario (MRFS) and High-End Future Scenario (HEFS) climate change flow estimations are as per the OPW Climate Change Sectoral Adaptation Plan guidance.

Table 9-1 Present Day Design Flows for AEP

HEP	Qmed	Flows for AEP							
		50% (2)	20% (5)	10% (10)	5% (20)	2% (50)	1% (100)	0.5% (200)	0.1% (1000)
15_1358_3	1.67	1.67	2.31	2.76	3.27	4.02	4.70	5.47	7.74
15_1358_4	1.81	1.81	2.50	3.00	3.54	4.36	5.10	5.93	8.39
15_1358_6	2.22	2.22	3.07	3.68	4.34	5.35	6.25	7.27	10.29
15_1182_3	1.38	1.38	1.89	2.27	2.67	3.29	3.83	4.44	6.25
15_1182_7	1.56	1.56	2.14	2.57	3.02	3.71	4.33	5.02	7.07
15_1358_7	2.80	2.80	3.87	4.63	5.48	6.74	7.88	9.16	12.97
15_1212_7	2.47	2.47	3.55	4.36	5.26	6.66	7.90	9.37	13.83
15_827_4	4.72	4.72	6.12	7.09	8.09	9.54	10.75	12.09	15.79
15_1794_2	7.61	7.61	9.88	11.44	13.05	15.38	17.34	19.50	25.46
15_1358_6b [10]	0.26	0.26	0.36	0.43	0.51	0.62	0.73	0.85	1.20

Table 9-2 Mid-Range Future Scenario Flows for AEP

HEP	Qmed	MRFS Flows for AEP (+20%)							
		50% (2)	20% (5)	10% (10)	5% (20)	2% (50)	1% (100)	0.5% (200)	0.1% (1000)
15_1358_3	2.01	2.01	2.77	3.32	3.92	4.83	5.64	6.56	9.28
15_1358_4	2.18	2.18	3.00	3.60	4.25	5.23	6.12	7.11	10.07
15_1358_6	2.67	2.67	3.68	4.41	5.21	6.42	7.50	8.72	12.35
15_1182_3	1.66	1.66	2.27	2.73	3.21	3.94	4.59	5.33	7.50
15_1182_7	1.87	1.87	2.56	3.08	3.62	4.46	5.19	6.03	8.48
15_1358_7	3.36	3.36	4.64	5.56	6.57	8.09	9.46	11.00	15.57
15_1212_7	2.97	2.97	4.26	5.23	6.32	7.99	9.48	11.24	16.60
15_827_4	5.67	5.67	7.35	8.51	9.71	11.45	12.90	14.51	18.95
15_1794_2	9.14	9.14	11.85	13.73	15.66	18.46	20.81	23.40	30.56
15_1358_6b [10]	0.31	0.31	0.43	0.52	0.61	0.75	0.88	1.02	1.44

Table 9-3 High End Future Scenario Flows for AEP

HEP	Qmed	HEFS Flows for AEP (+30%)							
		50% (2)	20% (5)	10% (10)	5% (20)	2% (50)	1% (100)	0.5% (200)	0.1% (1000)
15_1358_3	2.17	2.17	3.00	3.59	4.24	5.23	6.11	7.11	10.06
15_1358_4	2.36	2.36	3.25	3.90	4.60	5.67	6.63	7.71	10.91
15_1358_6	2.89	2.89	3.99	4.78	5.65	6.95	8.13	9.45	13.37
15_1182_3	1.79	1.79	2.46	2.95	3.47	4.27	4.98	5.77	8.13
15_1182_7	2.03	2.03	2.78	3.34	3.93	4.83	5.63	6.53	9.19
15_1358_7	3.65	3.65	5.03	6.02	7.12	8.77	10.25	11.91	16.86
15_1212_7	3.21	3.21	4.62	5.67	6.84	8.65	10.27	12.18	17.98
15_827_4	6.14	6.14	7.96	9.22	10.52	12.40	13.98	15.72	20.53
15_1794_2	9.90	9.90	12.84	14.87	16.97	20.00	22.54	25.35	33.10
15_1358_6b [10]	0.34	0.34	0.47	0.56	0.66	0.81	0.95	1.10	1.56

[10] 15_1358_6b is included to provide context in relation to its contribution to the Ballyhale Tributary peak flow and its significance given observed flooding anticipated to be derived from this source. The flow is calculated pro-rata by area from HEP 15_1358_6 rather than estimation directly from physical catchment descriptors.

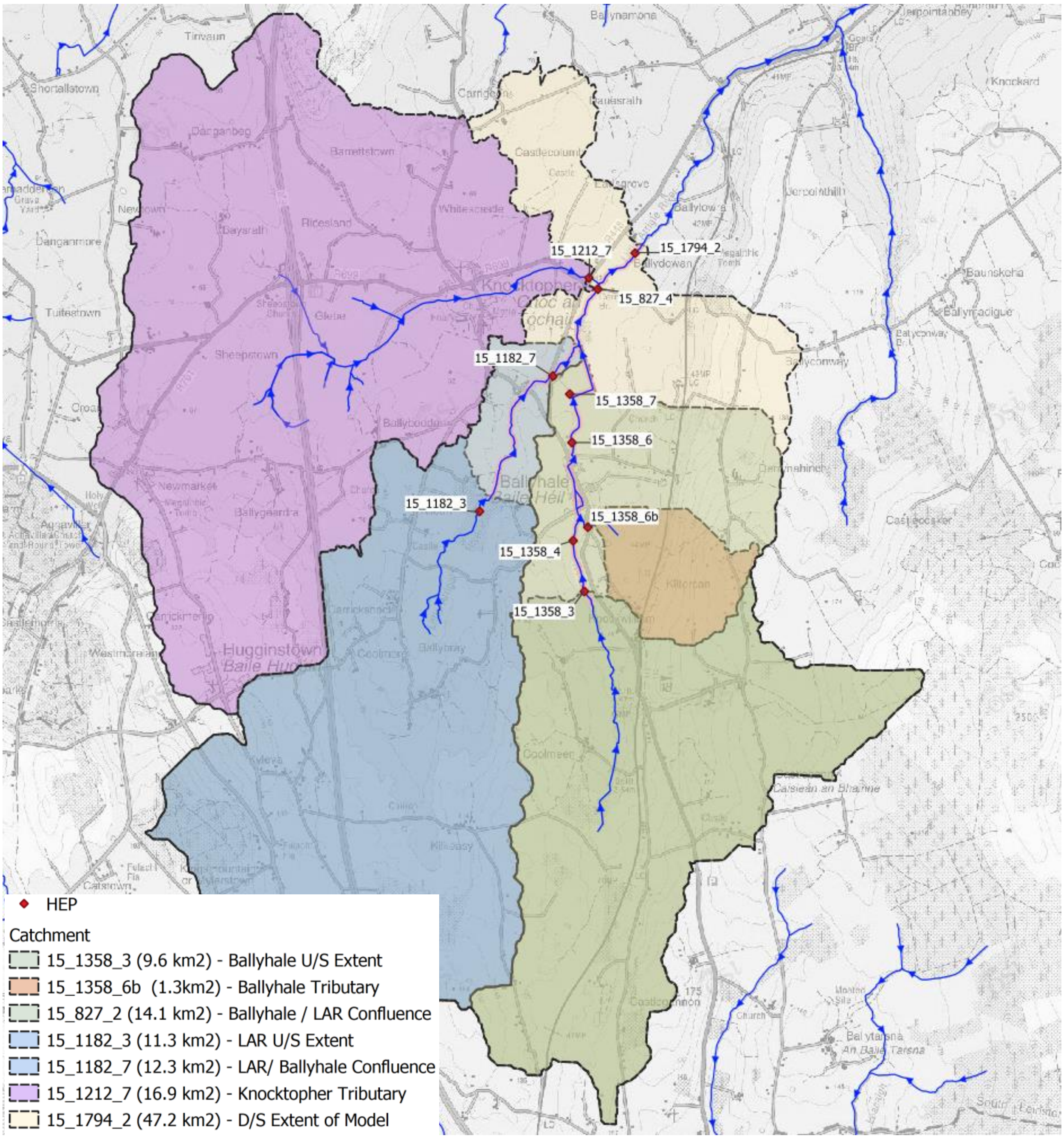


Figure 9-1 Model HEPs

9.2 Application to the Model

Flows between HEPs will be applied to the model using a combination of lateral (distributed) inflows and point inflows coinciding with tributary confluences indicated by the hydrological analysis. Subdivision of HEP catchments shall be on a pro-rata by catchment area basis from the peak for the respective HEP.

9.3 Hydrograph Shape

The FSU recommended methodology was adopted in the creation of the design hydrograph to apply flows to the model. Similarly, to deriving the index flow, hydrograph shape parameters are estimated for ungauged locations using pivotal catchments.

A hydrograph shape was generated for the Little Arrigle River downstream at the Knocktopher Confluence (15_827_4) for all flows on the Little Arrigle River and Ballyhale Rivers. Due to slight variance in catchment descriptors, a hydrograph shape was generated for the Knocktopher tributary using 13002 (Foulks Mill) pivotal.

The most hydrologically similar hydrograph pivotal site for each HEP (detailed in Table 9-4) was selected and used to adjust the hydrograph shape parameters at the subject site.

Table 9-4 Hydrograph Pivot Sites

Study HEP	Location	Hydrograph Pivot
15_827_4	Little Arrigle River (upstream of Knocktopher Confluence)	25022 - Syngefield
15_1212_7	Knocktopher Tributary	13002 – Foulks Mill

Design hydrograph shapes for Ballyhale / Little Arrigle and Knocktopher tributary within the model are shown in Figure 9-2. In this instance it is anticipated that, given the scale of the watercourses subject to the investigation, flooding will be primarily dictated by peak discharge rather than flood volume, and as such reduced significance is applied to the hydrograph shape and length.

The FSU hydrograph is influenced by large gauged catchments, as the study area is within a relatively smaller upstream 'flashier' catchment the hydrograph is likely to be an overestimate in terms of flood volume.

Initial consideration of the options for the scheme indicate that upstream storage / natural water retention is unlikely to be considered as part of the option assessment. In the instance that a storage option is achievable the option will be stress tested with a hydrograph with longer receding limbs.

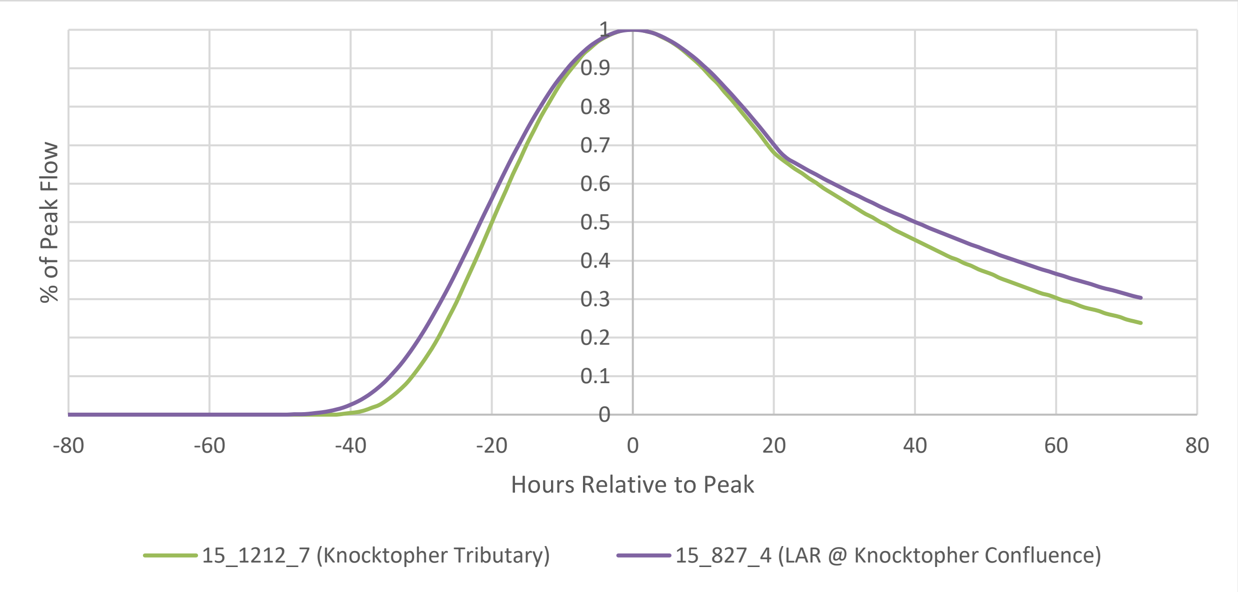


Figure 9-2 Design Hydrograph Shapes

10 CONCLUSIONS

The hydrological analysis is informed by a proposed hydraulic model extent designed to ensure coverage of Ballyhale village and all key receptors.

A search for historic records of previous flood events was undertaken, however only anecdotal evidence was uncovered and no specific dates or evidence (time-stamped photographs, recorded flood levels etc) was found. The catchment is ungauged. There is no sufficiently detailed historic flood record that would permit reliable hydrological or hydraulic calibration of hydrology for the study area.

A screening assessment of flood risk in Ballyhale indicates that recorded flooding historically appears to have been mainly influenced by fluvial flooding and the likely additional effect of culvert blockage. Reports of flooding along the main street originating from ‘Sheff’s Lane’ are assessed as most likely arising from out of bank flooding of an upstream unmapped tributary of the Ballyhale River; the flood mechanism will be appropriately captured and assessed by the fluvial hydraulic model.

Assessment of the historic flooding records and catchment characteristics has concluded that a catchment-based fluvial estimation approach is deemed the most appropriate approach for estimation of fluvial flood risk for the Study Area.

A fluvial hydrological analysis based on updated physical catchment descriptors has been undertaken, including verification of the river network. A detailed analysis of index flood estimation has determined that the FSU method remains the preferred method for all HEPs considered. The geographically closest (Centroid) pivot (15001 Annamult) estimate is deemed appropriate for use.

Growth curves previously calculated during the CFRAM study were adopted due to the inclusion of additional ‘flood rich’ water years in the CFRAM study which have not been updated to the FSU portal. Cursory analysis of water years data from the EPA HydroNet portal indicate that the additional water years between the CFRAM study and this study are unlikely to significantly distort the dataset.

Hydrograph shape was created using the FSU recommended methodology to apply flows to the model. Due to the similarity in catchment descriptors, a single hydrograph shape was adopted for all flows on the Little Arrigle and Ballyhale Rivers. A separate hydrograph shape was generated for the Knocktopher tributary inflow due to a more pronounced difference in catchment characteristics.

Flows will be applied to the model using a combination of lateral (distributed) inflows and point inflows coinciding with tributary confluences indicated by the hydrological analysis. Subdivision of HEP catchments shall be on a pro-rata by catchment area basis from the peak for the respective HEP.

HEP peak flows to be taken forward to the hydraulic modelling exercise are shown at Table 9-1, Table 9-2, and Table 9-3 for present day, mid-range future climate change and high-end future climate change scenarios respectively. Hydrograph profiles adopted are shown at Figure 9-2.

Given the ungauged nature of the catchment, the hydraulic analysis will include robust sensitivity testing of any preferred option to ensure that freeboard is resilient is potential for hydrological underestimation.