South Western CFRAM Study

Final Hydraulics and Flood Mapping Report,
Unit of Management 19

June 2016

The Office of Public Works

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Oifig na nOibreacha Poiblí

SOUTH WESTERN CFRAM STUDY
CATCHMENT FLOOD RISK ASSESSMENT AND MANAGEMENT

Mott MacDonald

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Issue and revision record

Revision	Date	Originator	Checker	Approver	Description	Standard
A	July 2014	M Piggott	R Gamble	R Gamble	Draft	
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Contents

Executive Summary

The Office of Public Works (OPW) is undertaking six catchment-based flood risk assessment and management (CFRAM) studies to identify and map areas with existing and potential future flood risk across Ireland. Mott MacDonald Ireland Ltd. has been appointed by the OPW to assess flood risk and develop flood risk management options in the South Western River Basin District. This hydraulics and flood mapping report is one of a series of reports being produced as part of the South West Catchment Flood Risk Assessment and Management Study (SW CFRAM Study). It details the development of the hydraulic models used to map current and future flood risk across Unit of Management 19. The model results and flood maps from this report inform the subsequent strategic environmental assessment and flood risk management plans.

Four hydraulic models have been developed for UoM19 as follows:

- I18BY Covering Ballingeary and Inchigeelagh Areas for Further Assessment (AFAs);
- I19CR Covering Castlemartyr and downstream to the Womanagh;
- I20KL Covering Killeagh and downstream to Womanagh; and,
- I21WH Covering the River Womanagh Medium priority Watercourse from Ladysbridge to the Sea

The hydraulic assessment and flood mapping for the remainder of UoM19 has been completed as part of the Lee Pilot CFRAM Study in 2013.

The river channels have been modelled using 1D ISIS software to calculate flows and head loss at hydraulic structures. The 2D TUFLOW software has been used to simulate the multi-directional flows across the urban floodplains of Castlemartyr and Killeagh. The 1D and 2D components of the models are hydrodynamically linked such that water can flow between the river and floodplain during the event to simulate the observed flood mechanisms. A 1D approach has been taken in Ballingeary and Inchigeelagh because the floodplain flow was deemed to be parallel to and fully connected with the channel flow.

The Ballingeary, Inchigeelagh and Castlemartyr were calibrated to the flood events of 19th November 2009 at Ballingeary, Inchigeelagh and Castlemartyr AFAs. The Killeagh and Womanagh models were not calibrated due to a lack of flood report, extents, levels and gauge information. However, sensitivity tests were undertaken on flow, downstream level and Manning's 'n' for all models.

The calibrated and tested models were then run for eight flood probabilities under the current design scenario, eight flood probabilities under the mid-range future scenario, and three flood probabilities under the high end future scenario from both fluvial and coastal sources. Each scenario considers the joint probability between fluvial sources of both the main river and tributaries in Ballingeary, Inchigeelagh, and Womanagh; and between fluvial and coastal sources on the Womanagh. Joint probability between different fluvial sources was not considered for Castlemartyr and Killeagh because there are no tributaries within the Areas for Further Assessment.

The flood extent, flood zone, flood depth, flood velocity and flood hazard have all been mapped for the specified scenarios, and are provided in the Appendices to this report.

The findings from the modelling results and flood maps will be used as inputs to the flood risk review. The knowledge of the flood mechanisms, critical structures and impact of flooding established in this report will support the development of sustainable and appropriate flood risk management options in the flood risk areas.

1 Introduction

1.1 The CFRAM Process

Flooding is a natural process that occurs throughout Ireland as a result of extreme rainfall, river flows, storm surges, waves, and high groundwater. Flooding can become an issue where the flood waters interact with people, property, farmland and protected habitats.

The Office of Public Works (OPW) is the lead agency in implementing flood risk management policy in Ireland. Mott MacDonald Ireland Ltd. has been appointed by the OPW to undertake the Catchment Flood Risk Assessment and Management Study (CFRAM Study) for the South Western River Basin District, henceforth referred to as the SW CFRAM Study. Under the project, Mott MacDonald will produce Flood Risk Management Plans which will set out recommendations for the management of existing flood risk in the Study Area, and also assess the potential for significant increases in this risk due to climate change, on-going development and other pressures that may arise in the future.

The South Western River Basin District is split into five Units of Management (UoM). These Units follow watershed catchment boundaries and do not relate to political boundaries. The Units are as follows;

- The Blackwater catchment (UoM18)
- The Lee / Cork Harbour Catchment (UoM19)
- The Bandon / Skibbereen Catchment (UoM20)
- The Dunmanus / Bantry / Kenmare Bay Catchment (UoM21)
- The Laune / Maine / Dingle Bay Catchment (UoM22)

Map 1.1 displays the extent of UoM19 which is the subject of this report. The hydraulic modelling and mapping of UoM19 under the SW CFRAM study includes four Areas for Further Assessment (AFAs) and 35km of modelled watercourses.

The AFAs include Ballingeary, Inchigeelagh, Castlemartyr and Killeagh. Both Ballingeary and Inchigeelagh were previously considered as part of the Lee Pilot CFRAM Study (2013), but were not previously classified as AFAs. This report undertakes more detailed hydraulic and mapping analysis for Ballingeary and Inchigeelagh to assess these towns as AFAs following feedback from the OPW and Cork County Council.

The hydraulic assessment and flood mapping for the remainder of UoM19 has been completed as part of the Lee Pilot CFRAM Study in 2013.

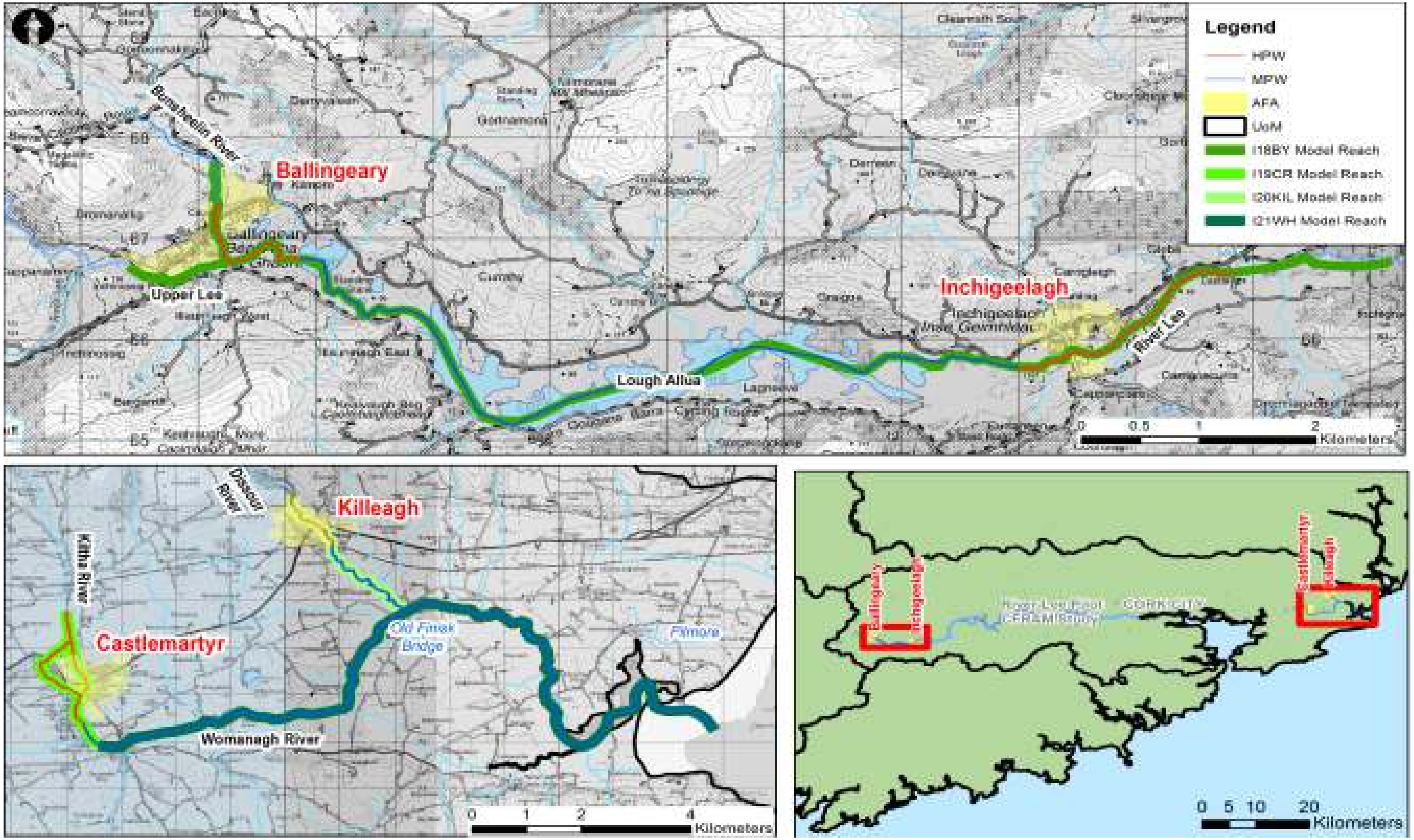
The overarching aims of the SW CFRAM Study are as follows:

- Identify and map the existing and potential future flood hazard;
- Assess and map the existing and potential future flood risk; and,
- Identify viable structural and non-structural options and measures for the effective and sustainable management of flood risk in the South Western River Basin District.

In order to achieve the overarching aims, the study is being undertaken in the following stages:

- Data collection;
- Hydrological analysis;
- Hydraulic analysis;
- Development of flood maps;
- Strategic Environmental Assessment and a Habitats Directive Appropriate Assessment;
- Flood risk assessment of people, economy and environment;
- Development and assessment of flood risk mitigation options; and,
- Development of the Flood Risk Management Plans (FRMPs).

Map 1.1: Unit of Management 19 Study Area



1.2 Report Structure

This report details the assessment of the hydraulic analysis and flood mapping at the following locations within Unit of Management 19:

- Ballingeary
- Inchigeelagh
- Castlemartyr
- Killeagh
- The River Womanagh downstream of the River Kiltha.

This report does not review or update the hydraulic analysis or flood mapping for the wider Lee catchment which has been assessed the River Lee Pilot CFRAM Study (Completed 2013).

The objectives of this report are:

- To document the findings and conclusions of the topographic survey
- To document the analysis and assumptions taken to develop hydraulic models for the AFAs and MPWs
- To map existing and potential flood hazard for the design scenarios
- To use the hydraulic models and maps to assess existing and potential future flood risk, and make recommendations for feasible flood risk management options and future modelling.

The main report outlines the generic approach to the hydraulic modelling and mapping. Detailed analysis and discussion of hydraulic modelling and mapping for each Area for Further Assessment (AFA) is provided in the Appendices. Table 1.1 outlines the report structure and scope of work with a description of the key contents.

Table 1.1: Report Structure

Chapter	Key Contents of Chapter
1. Introduction	▪ The SW CFRAM process ▪ Report structure ▪ Flood probabilities
2. Data Collection, Survey and Review	▪ Summary of data sources ▪ Review of all topographical and land cover data used
3. Hydrological Approach	▪ Summary of design inflows and downstream conditions ▪ Summary of joint probability ▪ Integration of design hydrology into the hydraulic model
4. Hydraulic Modelling Approach	▪ Discussion of general schematisation ▪ Discussion of overarching methodology for modelling river channels, key structure types and the floodplain ▪ Model parameters
5. Calibration and Sensitivity Analysis	▪ Discussion of calibration events ▪ Discussion of sensitivity tests on key parameters
6. Design Runs and Model Performance	▪ List of design runs ▪ Discussion of model convergence and performance
7. Assumptions and Limitations	▪ The key limitations and assumptions of the models and data
8. Flood Mapping Approach	▪ Discussion of the flood mapping process ▪ The types of flood hazard and specific flood risk maps and how these were calculated.

Chapter	Key Contents of Chapter
9. Model and Mapping Results	▪ Discussion of flood mechanism, frequency of flood issues, risk to life, critical structures, sensitivity to assumptions and guidance on flood risk management options for each AFA.
10. Summary and Recommendations	▪ Conclusions and key findings from the hydraulic analysis ▪ Summary of flood hazard in the Unit of Management ▪ Recommendations for flood mitigation option development Recommendations for future improvements in the hydraulic modelling

1.3 Flood Probabilities

The SW CFRAM Study refers to flood probabilities in terms of annual exceedance probability in preference to the use of "return periods" as used in previous reports. The probability or chance of a flood event occurring in any given year can be a useful tool to better understand the rarity of events of specific magnitude for flood risk management. Due to popular descriptors of floods involving terms like the "1 in 100 year flood" there can be public misunderstanding that a location will be safe from a repeat event of the same magnitude, extent and volume for the duration of the term (100 years in the above example). In reality, flood events of a similar or greater magnitude can occur again at any time.

Annual Exceedance Probability, henceforth referred to as AEP, is a term used throughout this report and the wider CFRAM studies to refer to the rarity of a flood event. The probability of a flood relates to the likelihood of an event of that size or larger occurring within any one year period. For example, a 1 in 100 year flood has a chance of one in a hundred of occurring in any given year; 1:100 odds of occurring in any given year; or a 1% likelihood of occurring. This is described as a 1% annual exceedance probability (AEP) flood event. Table 1.2 converts the 'return periods' to %AEP for key flood events as a reference to previous studies.

Table 1.2: Flood Probabilities

% Annual Exceedance Probability (%AEP)	Odds of a Flood Event in Any Given Year	Chance of a Flood Event in Any Given Year or Previous 'Return Period'
50%	1:2	1 in 2
20%	1:5	1 in 5
10%	1:10	1 in 10
5%	1:20	1 in 20
2%	1:50	1 in 50
1%	1:100	1 in 100
0.5%	1:200	1 in 200
0.1%	1:1000	1 in 1000

The hydraulic analysis and flood mapping uses a number of other acronyms and technical terminology which are defined in the glossary of this report.

2 Data Collection, Survey and Review

2.1 Data Collection and Review

A range of different data sources have been used to undertake the hydraulic analysis for the SW CFRAM Study. Table 2.1 lists the data used in Unit of Management 19 and the confidence in each dataset based on the review is discussed in the following sections.

Table 2.1: Summary of Data Used

Type	Details	Owner	Date Captured
Geometric Survey Data	River channel and structure survey and photographs of the Womanagh catchment.	OPW	As part of this study 2012-2013
	River channel and structure survey and photographs of the upper Lee including Ballingeary	OPW	2007
Detailed Digital Terrain Models	Filtered LiDAR data for Castlemartyr and Killeagh	OPW	2012
	Filtered LiDAR data for the Upper Lee	OPW	2006
National Height Model	IFSAR coarse elevation data with national coverage	OPW	2010
OSI Mapping	Building footprints and vector data of land cover	OSI	2010

The specific details of the data used for each model are included in the model Appendices.

2.2 Geometric Survey Data

As part of this study, extensive river channel survey was undertaken of all the High Priority Watercourses (HPWs) and Medium Priority Watercourse (MPWs) in the Womanagh catchment between December 2012 and February 2013 by Murphy Surveys Ltd (Map 2.1). The existing Ballingeary survey by Maltby Land Surveys Ltd (June 2007), which was undertaken for the Lee Pilot CFRAMs, was used directly for the Ballingeary Model. The survey captured topographic information about the elevations, dimensions and hydraulic conditions of the river channel and hydraulic structures. The detailed location of each cross-section is displayed in the model geoschematics provided at the end of the model build proformas in the Appendices. The detailed South West CFRAM Contract 5 Survey is available in a separate report (August 2013).

The following quality assurance of the survey data was also undertaken as part of the hydraulic analysis:

- Sections were surveyed from left bank to right bank facing downstream;
- Sections at the structure face were surveyed parallel to the structure and the skew angle recorded;
- Identification of any gaps and anomalies in the survey drawings or hydraulic model-formatted files;
- Analysis of changes and consistency with any other recent survey data.

The river channel survey was found to be surveyed from left to right bank and in parallel with structures, in accordance with the survey specification. Therefore, bed levels and low flow channel shape were linearly interpolated from the upstream and downstream sections. This assumption ensures that:

- The bed is not artificially elevated due to missing data; and,
- These sections do not act as hydraulic weir controls when the flow through is sub-critical in reality.

The geometric survey data captured in the Womanagh catchment was reviewed, with checks carried out on 10% of the cross sections. Using GPS survey equipment spot levels checks were carried out on structures and cross sections captured by the surveyor. The levels were reviewed and differences compared at bank crest. The average difference between the levels of the survey and the spot checks was found to be 0.14m in UoM19. This is considered to be a good correlation when considering that the comparison points were mostly on rough ground in rural areas. The exact locations are difficult to replicate, and the bank crest could vary or settle where they comprise of natural materials.

2.3 Digital Terrain Model Data

As part of this study, an aerial LiDAR (Light Detection And Ranging) survey was captured for each AFA as a point cloud with an average of 2 points per square metre (Map 2.2). The LiDAR data was captured in August 2006, May 2012 and September 2012 for the Upper Lee, Castlemartyr and Killeagh respectively. Subsequently, the raw LiDAR was collated to produce a digital surface model and post-processed to produce a bare-earth or Digital Terrain Model (DTM) by removing artificial structures, including buildings walls and bridges, and vegetation such as trees and hedges. The DTMs were processed for grid resolutions of 2m, 5m and 10m based on the same raw data.

The LiDAR DTM was compared with the validated survey for large flat surfaces, typically located along roads and hard-standing, or flat pasture where hard-standing was limited. It was deemed within 0.1m of the surveyed levels. Therefore the LiDAR DTM was deemed appropriate for use without further adjustment.

LiDAR was not available for the lower reaches of the Womanagh. Therefore, IfSAR data from the Intermap national height model has been used to create the DTM for hydraulic modelling and flood mapping. IfSAR has a lower vertical accuracy than LiDAR of ± 0.7m nationally. Along the Womanagh, the IfSAR was found to be +0.5m greater than the validated topographic survey on average. Therefore, the IFSAR data was adjusted by 0.5m to meet the river channel survey points and then joined with the LiDAR data(where available) to create a complete DTM.

Every effort has been made to ensure a consistent transition from LiDAR to IfSAR but dense vegetation around the Dower confluence resulted elevations being out by ~ 2m. Therefore additional manual smoothing was undertaken to linearly interpolate over the uncertain areas based on the LiDAR upstream and topographic survey downstream. There remains a greater uncertainty in this area and flood extents in are should be treated with caution due to the assumptions taken in the manual smoothing.

The raised embankments in the Lower Womanagh are not well represented in the IfSAR data. Therefore detailed geometric survey of the embankment crest has been used to inform the spill levels in the hydraulic model rather than the IfSAR DTM. Hence we can be confident in the spill threshold and level of flood risk in this reach.

2.4 Land Cover Data

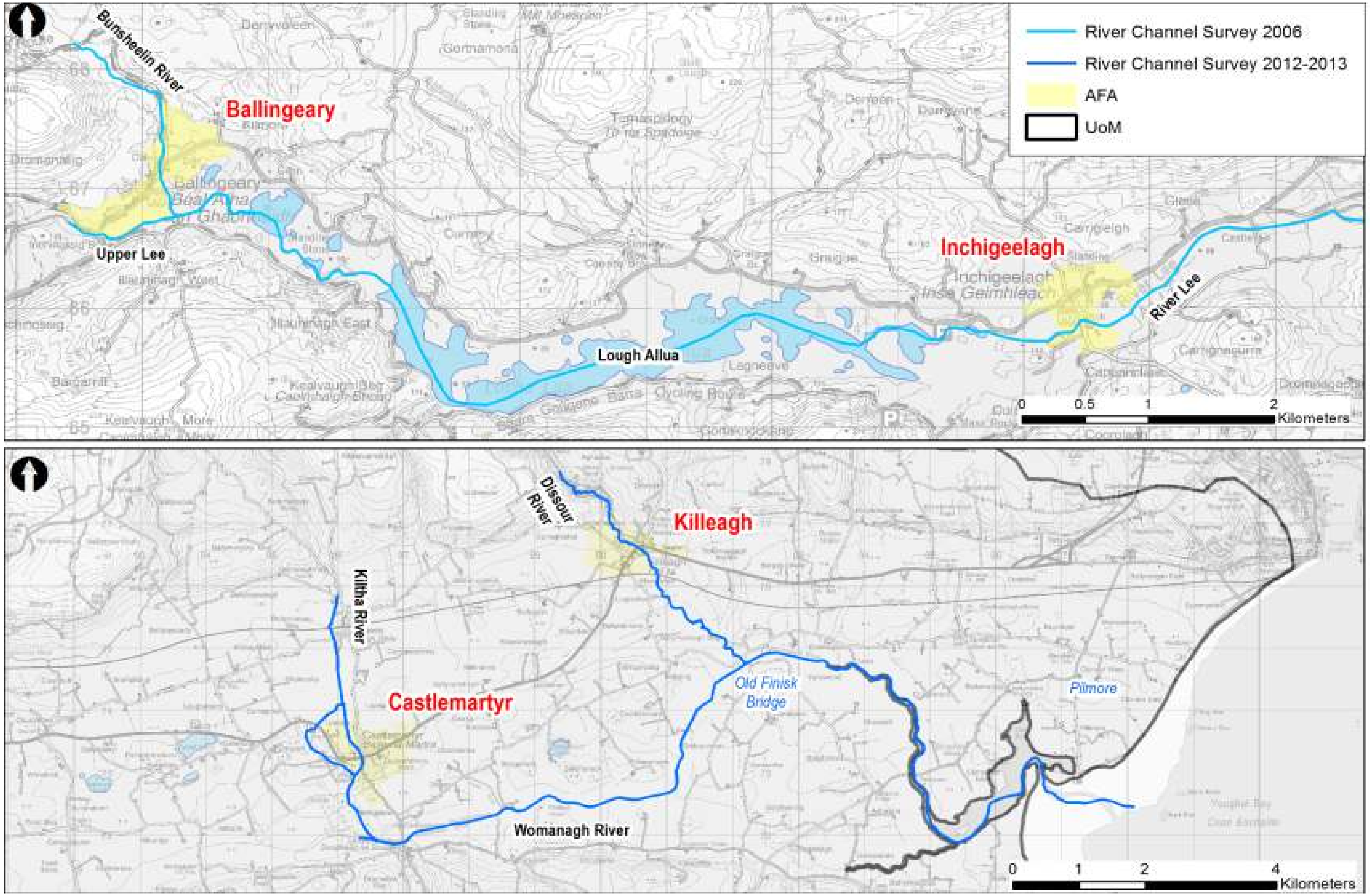
The various types of surfaces in the AFAs were assessed from the following data sources to inform the hydraulic roughness parameters for modelling:

- Building footprints derived from OSI mapping
- 1:1000,1;2500 and 1:5000 vector OSI Mapping
- Surface cover detailed in the geometric survey and survey photographs
- Site visits

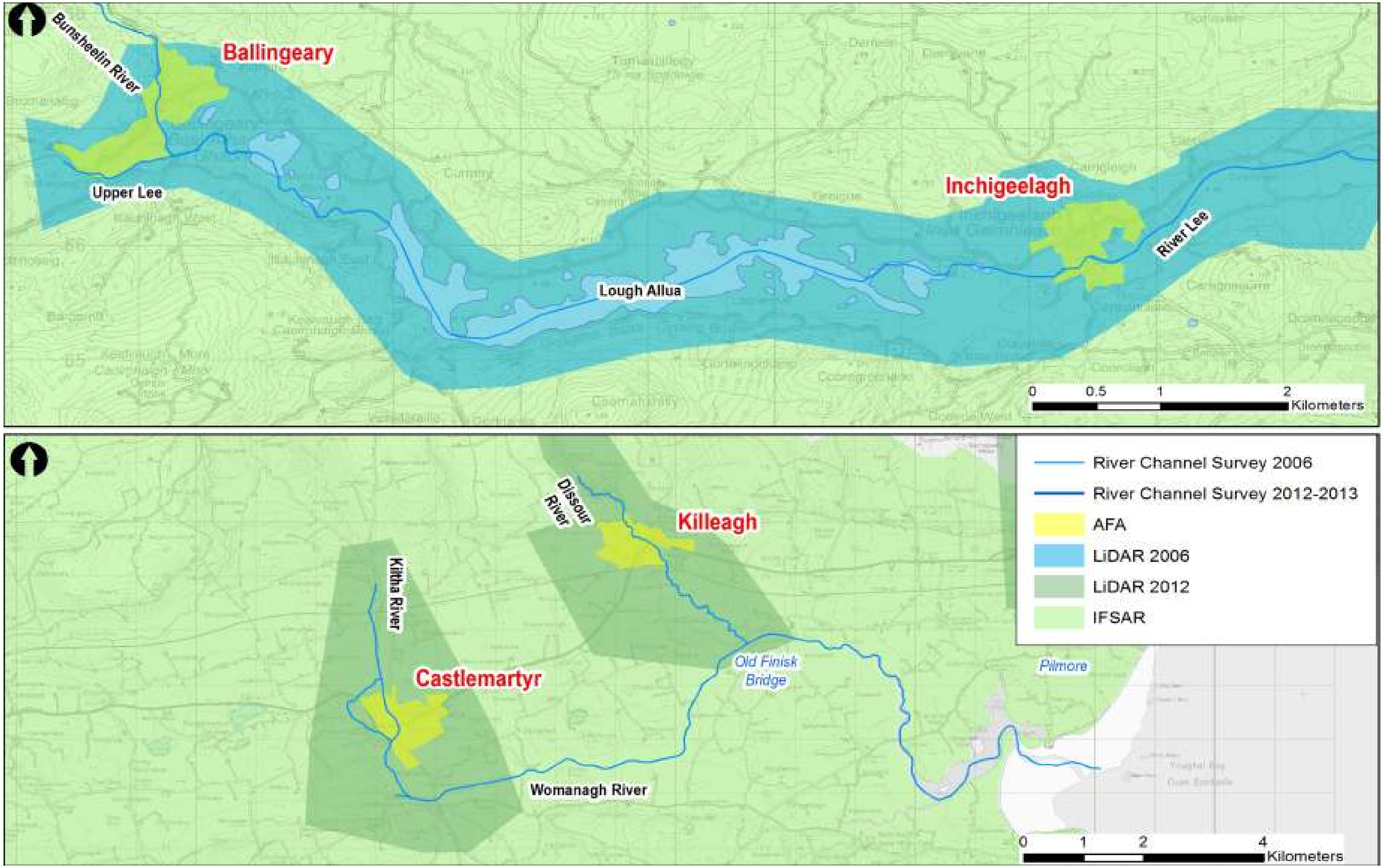
The mapping datasets were used in the first instance to classify land cover within each AFA into broad surface types of river bed and standing water; river banks; dense vegetation; pasture, parkland and arable; buildings; and, hard-standing urban areas. The land cover was subsequently refined during the model build process using the survey and site observations. The resultant detailed land cover for each AFA is provided in the Appendices.

The European Environment Agency CORINE land cover dataset was not used because the data is based on satellite imagery which is relatively coarse and does not differentiate buildings from surrounding roads and gardens within urban areas. Therefore, the more detailed OSI mapping was used in urban areas in conjunction with site observations.

Map 2.1: River Channel Survey Coverage in UoM19



Map 2.2: LiDAR Coverage in UoM19



3 Hydrological Approach

3.1 Summary of Design Hydrology

As part of the previous UoM19 Hydrology Report, design peak flows and hydrographs were derived at hydrological estimation points for the 50%, 20%, 10%, 5%, 2%, 1% , 0.5% and 0.1%AEP fluvial flood events.

The hydrological estimation points were located in every AFA and along the MPWs downstream. The HEP were located at the inflows to the hydraulic models, upstream and downstream of confluences with significant tributaries, and at the downstream limit of the hydraulic models. New HEPs were also derived for Ballingeary and Inchigeelagh to revise the peak flows and flood hydrographs from the previous Lee Pilot CFRAM Study (2011). Catchment descriptors were extracted from the FSU database and checked against the National Height Model, OSI contours and site observations. For smaller catchments not available in the FSU database, the catchment descriptors were derived from the difference between the upstream and downstream points and checked against the available data.

The design peak flows were derived using the recommended statistical method outlined in FSU Work Packages 2.2 and 2.3, and adjusted using the hydrological similar pivotal sites of 19020, 22009, 22022 and 25034. The White Gauge of 22009 was used to derive QMED in Castlemartyr and Killeagh. However the gauge was not deemed suitable to estimate extreme flows above QMED. Table 3.1 summarises the design peak flows for each catchment in the AFAs for ease of reference.

Table 3.1: UoM19 Design Peak Flood Flows at Key Locations

HEP	Gauge	Flow (m^3/s)							
		50%AEP	20%AEP	10%AEP	5%AEP	2%AEP	1%AEP	0.5%AEP	0.1%AEP
Ballingeary and Inchigeelagh AFAs									
19_927_2	Bunsheelin at Lee Confluence	24	30	34	39	45	51	57	76
19_928_2	Upper Lee – Bunsheelin Upstream	39	49	56	63	74	83	94	125
19_925_1	Upper Lee – Bunsheelin Downstream	63	79	90	102	120	135	152	202
19_1714_2	Upper Lee downstream of Lough Allua	74	93	107	121	142	161	182	242
19_1432_3	Tributary to Inchigeelagh	6.0	7.5	8.6	9.8	11.5	13.0	14.7	19.5
19_869_1	Upper Lee Downstream of Inchigeelagh	80	101	115	131	154	174	197	261
Castlemartyr AFA									
19_1909_9	Kiltha upstream	7	9	10	11	13	15	17	23
19_1909_15	Kiltha at Castlemartyr	9	11	12	14	17	19	21	28
19_1909_17	Kiltha at	9	11	12	14	17	19	21	29

HEP	Gauge	Flow (m^3/s)							
		50%AEP	20%AEP	10%AEP	5%AEP	2%AEP	1%AEP	0.5%AEP	0.1%AEP
	Womanagh Confluence								
Killeagh AFA									
19_686_15	Dissour at Killeagh	10	12	14	16	18	21	23	31
19_1798_3	Dissour at Womanagh Confluence	12	15	17	19	22	25	29	38
Womanagh MPW									
19_1266_7	Womanagh upstream of the Kiltha	2	3	3	4	5	5	6	8
19_705_1	Womanagh downstream of the Kiltha	12	14	16	18	22	24	27	36
19_1823_1	Womanagh downstream of Ladysbridge	13	16	18	20	24	27	31	41
19_1833_1	Womanagh downstream of the Dower	16	20	23	26	30	34	39	51
19_1794_1	Womanagh downstream of the Dissour	31	38	44	49	58	65	74	98
19_1941_2+	Womanagh tidal outfall	33	41	46	53	62	70	79	104

The FSU WP 3.1 UPO-ERR-gamma curve was derived for the ungauged HEPs in Castlemartyr, Killeagh and the lower Womanagh based on physical catchment descriptors and adjusted based on the hydrologically similar hydrograph pivotal gauges of 14007 and 16005 to derive the design hydrograph shape for the ungauged HEPs. The design unit hydrograph was then scaled above baseflow to achieve the design peak flows.

Previous analysis as part of the Lee Pilot CFRAM Study was found to underestimate backwater and associated flood risk in Ballingeary compared with flood reports, particularly for the 19th November 2009 event. Therefore, the design flood hydrographs in Ballingeary and Inchigeelagh were derived using the FSSR16 rainfall-runoff methodologies calibrated based on rainfall for historic flood events. This resulted in a design flood duration of 43 hours and 93% runoff to replicate the equivalent volume and saturated conditions of known flood events since 2004. This longer duration represents the volume and duration of flooding experienced from these multi-peaked events.

Joint probability is discussed in Section 3.3 which determined the corresponding tidal conditions used in combination with the fluvial flows.

3.2 Summary of Design Coastal Conditions

The River Womanagh is tidally influenced under MHWS conditions up to the tidal limit at Gortnagark, 1.2km downstream of Old Finisk Bridge. Much of the flood risk in the lower reaches arises from extreme tidal events.

As part of the previous UoM19 Hydrology Report, design total tide plus surge levels and tidal hydrographs were derived at the outfall of the Womanagh (at Ring Point, Pilmore) for the 50%, 20%, 10%, 5%, 2%, 1%, 0.5% and 0.1%AEP coastal flood events. The total tide plus surge levels were extracted directly from the nearest ICPSS offshore point, in the absence of more detailed level data at the outfall of the Womanagh. The resultant design levels are provided in Table 3.2.

Table 3.2: UoM19 Design Total Tide Plus Surge Levels

Location	Source	Total Tide Plus Surge Level (mODM)							
		50%AEP	20%AEP	10%AEP	5%AEP	2%AEP	1%AEP	0.5%AEP	0.1%AEP
Womanagh outfall	ICPSS Point S31 (Youghal Bay ~ 2km offshore)	2.19	2.28	2.36	2.42	2.52	2.58	2.65	2.81

The design astronomic tidal curve was transferred from the primary port of Cobh based on the United Kingdom Hydrographic Office Admiralty Tide Tables. The design surge profile was derived from analysis of typical surge durations along the South West coast and scaled on top of the astronomic tide to meet the design total tide plus surge level above.

The fluvial flows used in combination with the extreme tide plus surge conditions are discussed in Section 3.3.

3.3 Joint Probability

The design flows on each river reach and total tide plus surge levels provided above have been derived independently of each other. In reality, there can be dependency between sources of flooding which can be described by the joint probability to achieve a target %AEP event. The CFRAM study considers the following joint probabilities:

- Fluvial-fluvial – Where a range of combinations of flow on a main river combines with flow on a tributary to generate a specific %AEP flood downstream.
- Fluvial-coastal – Where an approaching depression generates a storm surge which combines with a river flood to generate a specific %AEP flood at the coast.
- Tidal- Wave – Where an approaching depression generates a storm surge which combines with extreme wave to generate a specific %AEP flood at the coast.

Fluvial Dominant Events

The fluvial-fluvial dependence was guided by the methodology set out in Flood Studies Update Work Package 3.4. In UoM19, the joint probability between the main river and the tributaries was found to be largely dictated by the size of the incoming catchments relative to the main watercourse (Table 3.3). The joint probability %AEP on the smaller tributary inflows, such as the Dower and Dissour, tended to be the more frequent smaller events in order to achieve the target flow on the main watercourse.

In order to simplify the modelling process, the closest design AEP to the joint probability estimate was selected. The flow was interpolated where the joint probability was half way between two design AEPs. The resultant joint probabilities are provided in Table 3.3. Castlemartyr and Killeagh AFAs do not have tributary inflows. Therefore the intermediate flows are the same probability as the main river.

Coastal Dominant Events

The joint probability between fluvial and tidal flooding was also considered on the Womanagh MPW, as the only reach affected by coastal conditions. The extreme fluvial flow estimates at the outfall was assessed with the ICPSS total tide plus surge levels to derive the joint probability combinations between fluvial and coastal events based on the DEFRA FD2308_TR1 desk-based assessment tool in accordance with GN20[1]. The dependence of river flow and storm surge in these estuaries tended to be “well” to “strongly” correlated due to the orientation of the bays and catchments. This resulted in ten different combinations of fluvial flows and tide plus surge levels for each design %AEP.

Previous studies (Lee CFRAM Study, River Clyde Flood Management Strategy[2], River Thames T2100 studies) have undertaken extensive sensitivity testing on a range of different combinations of fluvial flows and tidal levels to generate the 0.5%AEP design event, and found the following two scenarios to be critical to the flood extent at the target 0.5%AEP event:

- 0.5%AEP fluvial flow combined with the MHWS tide; and
- 50%AEP fluvial flow combined with 0.5%AEP tide plus surge level.

Therefore, the SW CFRAM Study has taken a similarly pragmatic approach and limited the joint probability analysis to one fluvial dominate scenario and one tidally dominant scenario for models affected by both fluvial and coastal flooding (Table 3.4):

- Design %AEP fluvial flow combined with MHWS tide
- Design %AEP tide plus surge combined with 50% to 70%AEP fluvial flow

The Irish Coastal Water Level and Wave Study (ICWWS) did not identify any location vulnerable to wave overtopping for the UoM19 AFAs assessed as part of this study. Therefore, wave overtopping has not been considered any further.

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[1] RPS (2012) CFRAM Guidance Note 20, Joint Probability Guidance.

[2] Section 3.6 Lee CFRAM Hydraulics Report (2013)

Table 3.3: Summary of Joint Probabilities Used for Fluvial Dominant Events

Applicable Models	Overall %AEP (Fluvial Dominant Event)	Design Flood Event Occurs on	Main River Inflow %AEP	Typical Tributary River Inflows %AEP	Coastal %AEP (where applicable)
I18 BY Ballingeary-Inchigeelagh	50%AEP	Main River	50%	50%	N/A
		Tributary River	50%	50%	N/A
	20%AEP	Main River	20%	50%	N/A
		Tributary River	50%	20%	N/A
	10%AEP	Main River	10%	20%	N/A
		Tributary River	20%	10%	N/A
	5%AEP	Main River	5%	20%	N/A
		Tributary River	20%	5%	N/A
	2%AEP	Main River	2%	10%	N/A
		Tributary River	10%	2%	N/A
	1%AEP	Main River	1%	5%	N/A
		Tributary River	5%	1%	N/A
	0.5%AEP	Main River	0.50%	2%	N/A
		Tributary River	2%	0.50%	N/A
	0.1%AEP	Main River	0.10%	1%	N/A
		Tributary River	1%	0.10%	N/A
I19CR Castlemartyr I20 Killeagh	50%AEP	Main River	50%	N/A	N/A
	20%AEP	Main River	20%	N/A	N/A
	10%AEP	Main River	10%	N/A	N/A
	5%AEP	Main River	5%	N/A	N/A
	2%AEP	Main River	2%	N/A	N/A
	1%AEP	Main River	1%	N/A	N/A
	0.5%AEP	Main River	0.50%	N/A	N/A
	0.1%AEP	Main River	0.10%	N/A	N/A
I21WH Womanagh	50%AEP	Main River	50%	50%	MHWS
		Tributary River	50%	50%	MHWS
	20%AEP	Main River	20%	50%	MHWS
		Tributary River	50%	20%	MHWS
	10%AEP	Main River	10%	20%	MHWS
		Tributary River	20%	10%	MHWS
	5%AEP	Main River	5%	20%	MHWS
		Tributary River	20%	5%	MHWS
	2%AEP	Main River	2%	10%	MHWS
		Tributary River	10%	2%	MHWS
	1%AEP	Main River	1%	5%	MHWS
		Tributary River	5%	1%	MHWS
	0.5%AEP	Main River	0.50%	2%	MHWS
		Tributary River	2%	0.50%	MHWS
	0.1%AEP	Main River	0.10%	1%	MHWS
		Tributary River	1%	0.10%	MHWS

Table 3.4: Summary of Joint Probabilities Used for Coastal Dominant Events

Applicable Model	Overall %AEP (Coastal Dominant Event)	Design Flood Event Occurs on	Main River AEP	Tributary River AEP	Coastal AEP
I21WH Womanagh	50%AEP	Coast	50%	71%	50%
	20%AEP	Coast	50%	71%	20%
	10%AEP	Coast	50%	71%	10%
	5%AEP	Coast	50%	71%	5%
	2%AEP	Coast	50%	71%	2%
	1%AEP	Coast	50%	71%	1.0%
	0.5%AEP	Coast	50%	71%	0.5%
	0.1%AEP	Coast	50%	71%	0.1%

3.4 Integration of Hydrology and Hydraulic Modelling

The design hydrological inflows summarised in Section 3.1 have been integrated with the hydraulic models as follows:

- Point inflows at the upstream model extents;
- Point inflows at key tributary inflows;
- Lateral inflows representing the inflow from the intervening areas between target HEPs.

The lateral inflows have been calculated from the difference between the design flow hydrographs from the upstream and downstream HEPs for a reach. The resultant hydrographs have been distributed evenly across those locations where the contributing area increases linearly downstream or area-weighted where the contributing area increases disproportionally downstream.

The point inflows representing the upstream model extents and tributary inflows were applied to the uppermost cross-sections in the hydraulic model. The inflow for the entire catchment was simplified and lumped at the upstream end of the model for the Bunsheelin catchment and Upper Lee in Ballingeary AFA because the intermediate catchment to their confluence was relatively small.

The lateral inflows have been integrated with the relevant cross-sections at locations which fit the following criteria:

- Natural inflows from minor watercourses which are not considered explicitly within the hydrology;
- Overland flow paths identified from surveyed low points in the river bank and site walkover;
- Reconciliation adjustments of hydrological flow estimates and hydraulic models.

The model proformas provided in the Appendices detail the location of each lateral inflow.

In order to enhance the modelling outputs and ensure hydrological continuity along the larger catchments, the hydraulic models were calibrated to the design peak flows derived at the target HEPs. The hydrological inflows were iteratively phased such that the hydraulic model maintains the design peak flows along the

reach as part of the hydraulic modelling process. However, it should be noted that the design fluvial flows do not consider the following hydraulic processes:

- Backwater effect at confluences;
- Exchange of flows between tributaries at confluences; and,
- Significant modification to the hydrograph shape due to floodplain attenuation and /or hydraulic structures.

Therefore, it was not appropriate to calibrate the hydraulic models to HEPs upstream of confluences where there are significant out-of-bank flows. Table 3.4 details the timing adjustments made to the inflow hydrographs to achieve the design peak flows at the target HEPS for each reach. The Dower and Ballying peak flows were shifted earlier because these karstic catchments take a longer time to peak.

Section 6.2 compares the resultant modelled flow against the design flows to assess model performance.

Table 3.5: Phasing of Inflows

Model	Sub-catchment	Time Shift Applied to the Inflow Hydrographs to Achieve the Design Peak Flows at the target HEPS (Hours)
Ballingeary and Inchigeelagh	Upper Lee	0.00
	Bunsheelin	1.25
	Inchigeelagh Tributary	6.50
Castlemartyr	Kiltha	0.00
Killeagh	Dissour	0.00
Womanagh	Kiltha	2.25
	Ladysbridge	0.0.
	Dower	-16.5
	Ballying	-16.5
	Dissour	0.00

The design tide plus surge hydrographs discussed in Section 3.2 were used to form the downstream boundary conditions for the hydraulic models. An iterative approach was used to phase the design tide plus surge hydrographs so that the peak tide coincides with the peak flow in the AFA. This phasing is a conservative assumption of combined flood risk in line with the joint-probability analysis in Section 3.3 above. Table 3.5 outlines the downstream conditions applied and time by which the tidal hydrograph was adjusted in order to meet the peak river flow.

Table 3.6: Downstream Boundary Conditions

Model	Downstream Condition	Time Adjustment to Coincide Peak Tide with Peak Flow (Hours)
Womanagh	Full tidal boundary at the downstream of the Womanagh	0

3.5 Critical Storm Duration

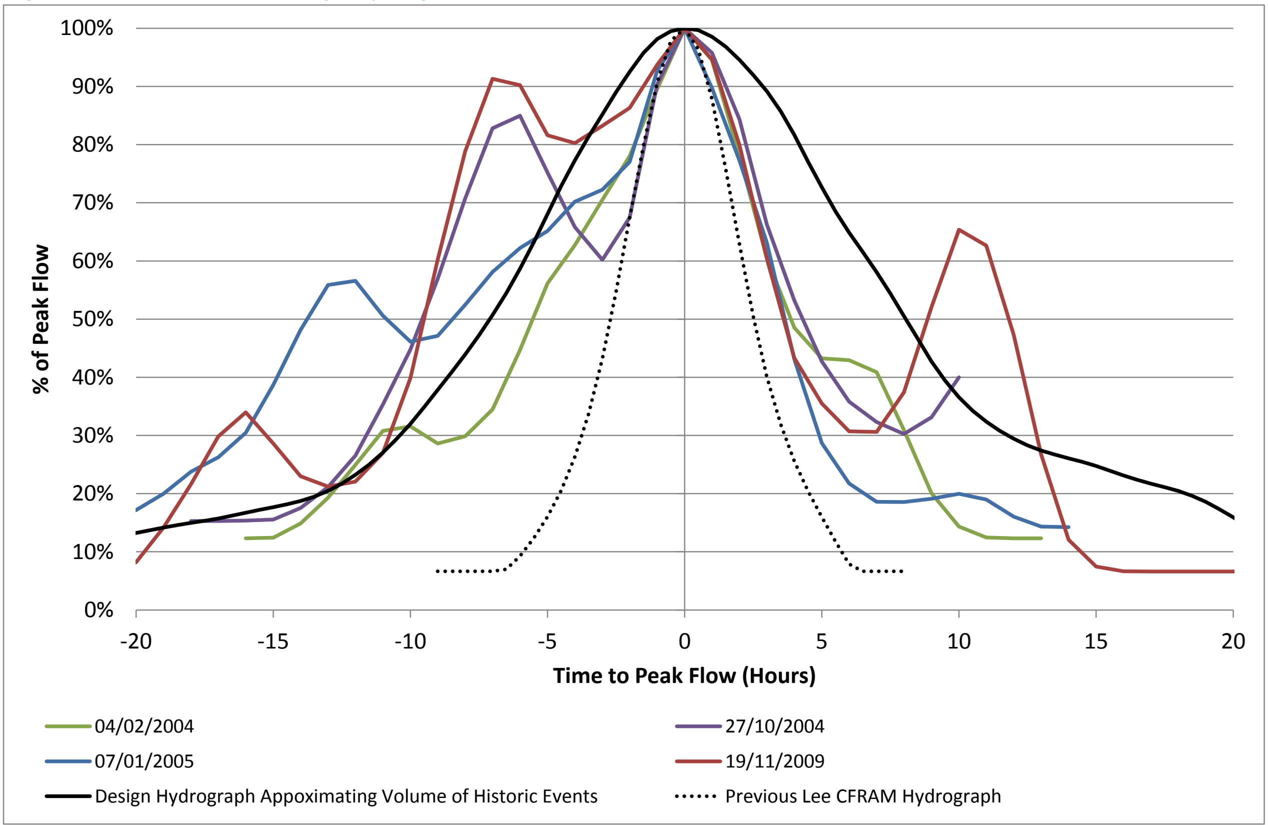
The design storm duration has been derived from the time to peak and SAAR applying the FSSR16 approach. The storm duration was adjusted to produce the critical hydrograph for each AFA assuming a single design storm event. The longer duration was adopted as a conservative estimate for the design scenario where the critical duration for independent sub-catchments varied within an AFA. This ensured a physically realistic single storm event in these small coastal catchments (< 30 km^2). Table 3.6 outlines the resultant critical durations for each AFA used for the design scenarios.

Table 3.7: Critical Storm Durations for Rainfall-Runoff Inflows

Model	Method	Theoretical Critical Duration (Hours)	Design Duration (Hours)
Ballingeary and Inchigeelagh	FSSR estimate	11	43 (approximating volume of historic events)
Castlemartyr	FSSR estimate	13	13
Killeagh	FSSR estimate	13	13
Womanagh	FSSR estimate	13	13

It should be noted that the design duration for Ballingeary and Inchigeelagh model is 43 hours on the main river to consider the equivalent volume that causes the water levels to rise in Lough Allua based on historic flood events (Figure 3.1) .The selected design event hydrograph/storm profile provides a significant increase in volume compared to the generic FSR rainfall-runoff approach critical duration hydrograph as used in the previous Lee CFRAM Study Pilot (Figure 3.1).

Figure 3.1: Bunsheelin Design Hydrograph



Section 5.2.4 of this report investigates the sensitivity of flood risk to this storm duration assumption.

4 Hydraulic Modelling Approach

4.1 Schematisation

Table 4.1 outlines the general approach for each AFA in UoM19. Map 4.1 presents the areas and reaches modelled.

Table 4.1: UoM19 Model Approach

Model ID	Location	Approach	No. Models	Area Modelled in 2D (km^2)	Length Modelled in 1D (km)	Upstream Limit	Downstream Limit
I18BY	Ballingeary AFA Inchigeelagh AFA	1D ISIS	1	N/A	10.0	115143,067768 114415,066720	122447,065895
I19CR	Castlemartyr AFA	1D/2D ISIS/ TUFLOW	1	2.6	6.0	196000,074643	196585,071925
I20KL	Killeagh AFA	1D/2D ISIS/ TUFLOW	1	1.4	3.8	200124,077165	202190,074769
I21WH	Womanagh MPW	1D ISIS	1	N/A	15.4	196585,071925	206695,073100

Modelling of AFAs

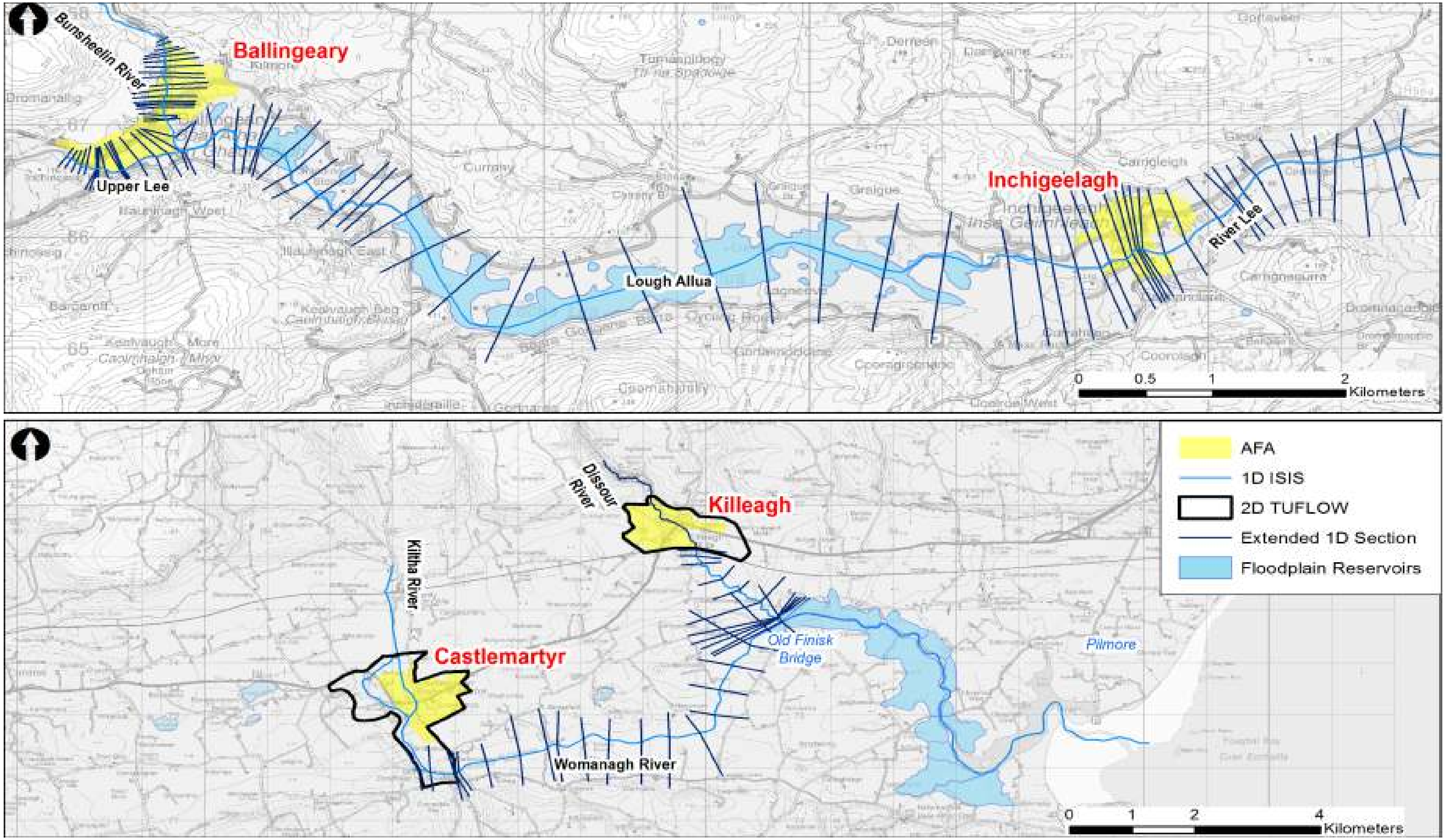
A hydrodynamically linked one-dimensional (1D) and two-dimensional (2D) approach has been taken for Castlemartyr and Killeagh. The HPWs have been modelled in ISIS 1D modelling software (version 3.6.0) to simulate in-bank flows as ISIS is capable of accurately calculating conveyance, attenuation and head loss at structures in narrow rivers. TUFLOW two-dimensional modelling software (version 2012-AC-05) has been used to model the floodplains in all the AFAs in order to simulate complex flow paths and variable velocities across the urban floodplains. The 2D approach is also the most appropriate to simulate flooding in urban areas, as it is able to simulate the multi-directional flow paths along roads and across the floodplain.

Ballingeary and Inchigeelagh have been modelled in the same hydraulic model in order to fully consider the routing of flow through Lough Allua. A 1D approach has been taken for Ballingeary and Inchigeelagh AFAs because the floodplain flow is parallel to the river channel and limited by the narrow valley. Therefore the 1D approach is deemed sufficient to assess flood risk to the AFAs.

Modelling of MPWs

The MPW reaches of the Womanagh have been modelled using ISIS to simulate both in-bank and out-of-bank flows using the river channel survey in-bank and by extending the river sections across the floodplain using topographic survey adjusted-SAR based DTM. Downstream of Finisk Old Bridge, the floodplain is largely disconnected from the tidal channel as there are raised embankments. Therefore, the raised embankments have been represented in the model by spills into the separate flood cells of the floodplain. The flood cell volumes are based on the IFSAR DTM to provide an estimate of floodplain volume. A more detailed 2D modelling approach was not used for the lower Womanagh because the floodplain elevations are reliant on less accurate IFSAR data, and therefore a 2D approach would not significantly improve flood depth information.

Map 4.1: Model Approach



4.2 River Channels

The 1D model components were developed to simulate in-bank flows between the left and right river banks. The river channel survey data was used to inform the river cross-sections in ISIS. The raw survey data did not require correction for the majority of sections in UoM19. However, the following modifications were made during the modelling process for open channel sections:

- In Inchigeelagh, river channel sections were manually interpolated for the reach downstream of Inchigeelagh Bridge with in-channel islands. These sections were based on LIDAR of the vegetated islands combined with original river channel survey.
- Assumptions on roughness and capacity of this reach were investigated as part of the sensitivity tests.
- Additional river channel sections have been automatically interpolated along the Bunsheelin Stream in Ballingeary and Kiltha River in Castlemartyr to stabilise flow over the steep gradients based on the surveyed and DTM slope.

The river channel gradient, width and shape can vary rapidly on the approach and exit of bridges, which is not necessarily representative of the typical open channel reach. Therefore, the surveyed sections observed 20m upstream and downstream of bridges tended to be used to inform the open channel modelled upstream and downstream of bridges because these survey sections tended to be more representative of the typical reach.

The exception are the road bridges in Castlemartyr and Killeagh, where the survey section immediately upstream of the bridges was deemed to be representative of the short reach upstream to the next structure.

Resistance to flow from varying surface roughness across the river channel was represented by various Manning's 'n' values based on the material type and vegetation density (Table 4.2). The material types were assigned based on the survey data, photographs and site observations. The selection of the Manning's 'n' value was guided by the industry standard value ranges (Chow 1959), and subsequently adjusted during the calibration process where data was available. The selected Manning's 'n' values for each model are summarised in the model build proformas and in the model section data.

For models applying the 1D approach (i.e. Ballingeary-Inchigeelagh and Womanagh), the cross-sections were extended based on the LiDAR DTM to represent the entire valley section. Floodplain reservoir units were used where the floodplain was disconnected from the channel by raised embankment in the Lower Womanagh to correctly represent parallel flow and offline storage on the floodplain.

Table 4.2: Summary of Channel Manning's 'n' Values

Material Type	Selected Manning's 'n'	Applicable Reaches
Active river bed with gravel to boulders	0.045 to 0.050	River Lee at Inchigeelagh and downstream reach
Active river bed with silts and gravels	0.040 to 0.045	River Lee and Bunsheelin River at Ballingeary and into Lough Allua Kiltha River Dissour River Womanagh River
Light brush and/or grass during winter	0.060 to 0.075	River Lee Kiltha River Dissour River Womanagh River
Dense vegetation year round	0.075 to 0.080	River Lee downstream of Inchigeelagh bridge for in-channel islands. Upper Kiltha River Upper Dissour River

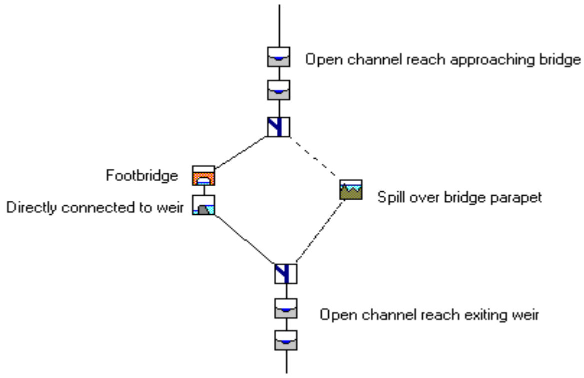
Source: Chow 1959

4.3 Structures

The surveyed structure dimensions were used to conceptualise bridges, culverts and weirs to simulate the hydraulic controls and flow paths that modify flood risk in the AFA. The conceptualisation sought to reduce complex structures to the simplest schematisation that accurately represented the hydraulic mechanisms at the target flows whilst maintaining model stability and robustness.

For example, many bridges in the South West Region have a plinth extending a short distance from the downstream face which causes a hydraulic jump similar to a weir at low flows (Figure 4.1a). The short open channel reach between the bridge and the weir is likely to cause instability at high flows as the reach is so much shorter than the other reaches in the 1D model, and connection to the 2D model may cause recirculation of water. Therefore, the model is simplified to the configuration in Figure 4.1b which maintains the weir as the level control at low flows but avoids instabilities at high flows.

Figure 4.1: Simplification of Kanturk Footbridge and Weir



A: Kanturk Footbridge with Weir 2m downstream B: Simplified Model Configuration

The simplification of structures in UoM19 is discussed in the following sections. There were no operable structures within the UoM19 AFAs. Full details of the hydraulic parameters and justification of structure specific assumptions can be found in Schedule 2 of the Model Build Proformas in the relevant appendices.

Bridges

Bridges have been modelled in three ways in the SW CFRAM Study:

- Using the USBPR approach where the bridge was a flat soffit highways bridge and the afflux was largely controlled by the flow around the piers and a spill over the deck to consider high flow routes.
- Using the HR Wallingford arched bridge approach where the bridge was arched and the afflux was largely controlled by the flow under the arch above springing point and a spill over the deck to consider high flow routes.
- Using a Bernoulli head loss unit based on the calculated head loss with the effects of piers, skew, eccentricity and other hydraulic losses.

The first two approaches were applied across UoM19 for this study. No Bernoulli Loss units were used to represent bridges in UoM19. Bridges in Inchigeelagh, Castlemartyr, and Killeagh were attached directly to a spill representing the drop in bed level across the structure as per the example in Figure 4.1.

Culverts

For the wider SW CFRAM Study, culverts modelled in ISIS use; i) a culvert inlet to simulate losses associated with the constriction of flow at the entrance ii) an appropriate sized and shaped conduit unit and iii) a culvert outlet to simulate losses associated with the expansion of flow at the exit, or a weir unit to simulate the bed drop for culverts out-falling above the downstream river water level. However, no culverts were surveyed or modelled in this study for UoM19.

Weirs

Formal weir structures such as those found in Castlemartyr and Killeagh and other informal weirs/natural bed drops, such as under bridges, have been modelled using weir and online spill approaches. For both formal and informal weirs, the river sections have been extracted 20m upstream and downstream of the weir structure based on the surveyed weir long profile to adjust the bed levels and better represent the upstream and downstream open channel reaches. Where the spill or weir represents a natural bed drop, the open channel section upstream was lowered 0.1m below the spill crest to stabilise the ISIS model. Therefore the natural bed level which forms the control is represented in the spill unit. The surveyed weir crest was then used to inform the width and elevation in the formal round-nose weir structures, and the spill elevations for informal structures. This approach ensures the weir or spill crest forms the hydraulic control and the localised scour pool effects are removed. Where the defined weir crest is narrower than the river channel width, online spills have been used to represent flow over the banks, with spill coefficients lowered to 0.9 to 1.3 (within the recommended range) to simulate the effects of bank vegetation and calibrated to spot gaugings at the gauging station where available.

4.4 Floodplain

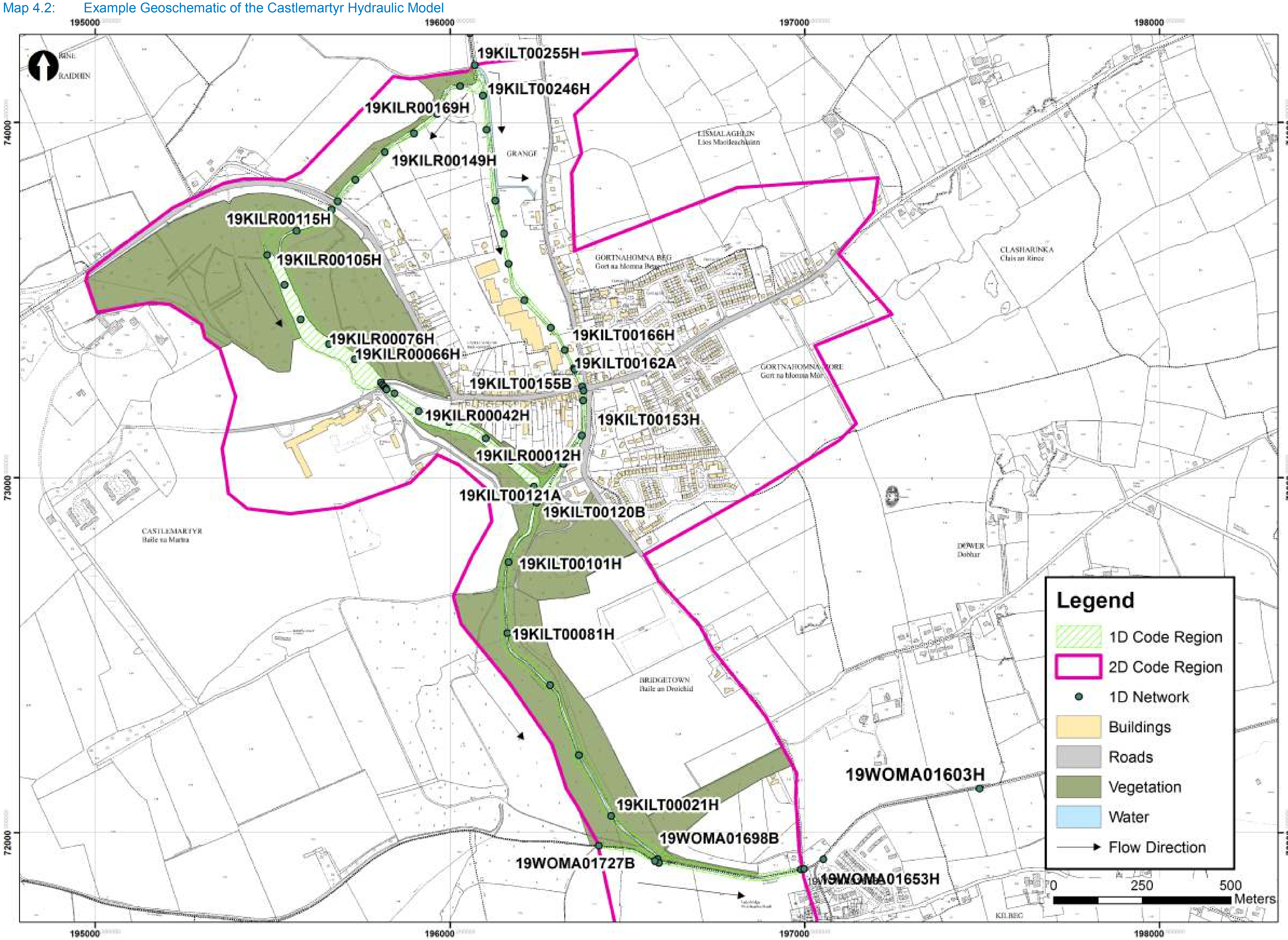
The floodplain in the Castlemartyr and Killeagh AFAs was represented by a regular 5m grid orientated to be perpendicular to the dominant flow path. A 5m grid cell size was selected as consistent grid cell size across the SW RBD to provide an acceptable resolutions and run time whilst adequately representing the complex urban nature of all these AFAs. The 2D grid cell size for smaller AFAs, such as Killeagh, could be refined further however it is limited by existing 1s timestep in the 1d elements and the 5m grid size adequately represent flow paths along roads for these AFAs. Map 4.2 presents an example for Castlemartyr.

Floodplain Topography

The 2D topography was extracted from the LiDAR DTMs. The 5m grid resolution does limit the representation of small and thin urban features. Therefore, key floodplain features that would modify flow paths have been explicitly represented in the 2D domain. This includes raised barriers to flow, such as road and rail embankments, as well as flow routes such as drainage ditches and archways through buildings. The elevations for these features have been extracted from the LiDAR data and enforced in the 2D domain using the “Z-line” option. Thin features, such as fences and garden walls, have not been considered, as they cannot be guaranteed to retain water during a flood event where they are not designed as flood defences.

In Castlemartyr, the drainage ditch towards the Enterprise centre has been enforced based on LIDAR elevations and using a lower Manning’s ‘n’ to represent this flow path. The sink hole at the end of this ditch and the sink hole on the other side of the road at 19KILTH00166H have been assumed to be saturated and no flow was abstracted from the model as a conservative estimate of flood risk in the AFA.

Map 4.2: Example Geoschematic of the Castlemartyr Hydraulic Model



N.B. White areas within the study area have been conceptualised as pasture/parkland/garden in reference to Table 4.3 Floodplain Roughness Values.

Urban Features

Buildings within the floodplain were represented as footprints with a threshold level of 150mm above ground level extracted from the DTM. The threshold of 150mm was selected as typical from threshold surveys and survey photographs. Once out-of-bank, flood extents are largely determined by the narrow valley topography and the raised building footprint does not significantly alter the floodplain capacity. Therefore, the threshold value selected does not significantly affect the flood risk and extent in the AFA. The buildings were assigned a Manning's 'n' value of 0.2 to simulate the reduction in flow and velocity through the buildings once water depth was above the threshold value of 0.15m. A Manning's 'n' value of 0.2 has been selected as the upper limit of industry standard values for floodplains.

Syme (2008)[3] tested different methodologies of representing buildings including blocking out, Manning's 'n' and cell blockage approaches. Syme found the increase in water levels due to the different representation of buildings were all within 0.04m of each other with a standard deviation of 0.03m (Table 3.2 Syme 2008).

The blocked out methodology presents a more "visually correct" representation of flow paths around the building but does not simulate the effects of storage within the building and does not produce a representative flood level. Therefore, the Manning's 'n' approach combined with the building threshold approach has been selected to represent the impact of building whilst providing a representative flood level for subsequent damage calculations. This approach assumes water is able to flow through the buildings which might otherwise be diverted if the building was made watertight, such as from the use of sandbags or individual property protection measures. The use of individual protection property measures, such as sandbags, has been considered when comparing model results with historic flood extents.

The roads in UoM19 are typically 6 to 8 m wide, and are neither significantly raised above nor sunken below the floodplain. Therefore, the model grid topography was deemed to represent the flow paths of the roads without further modification to the model topography. Instead, a lower Manning's 'n' of 0.03 was used to represent the relatively lower resistance to flow of the road surface. This approach enforces the roads as flow paths across the floodplain to better model flood progression.

Land Cover

The floodplain was classified into broad land use types from the survey information, photographs of the river banks, site observations and OSI mapping. The European Environment Agency CORINE land cover dataset was not used because the data is based on satellite imagery which is relatively coarse and does not differentiate buildings from surrounding roads and gardens within urban areas.

Each land classification from the OSI mapping was then assigned an appropriate Manning's 'n' roughness value based on the type and density of the vegetation, guided by industry standard value ranges (Chow 1959). A value of 0.030 was selected for roads and hard standing as a combined estimate for tarmac and

[3] Syme (2008) Flooding in Urban Areas - 2D Modelling Approaches for Buildings and Fences. Engineers Australia, 9th National Conference on Hydraulics in Water Engineering. Darwin Convention Centre, Australia 23-26 September 2008

gravel standing as the two land covers were not easily distinguishable in all locations. This value still provides a relatively lower roughness compared to the surrounding land cover making the roads the preferential flow path.

Small urban features, such as fences and walls, have not been considered explicitly as they are not designed to retain water during a flood event. However, the overall impact of these features has been incorporated into the selection of the upper range of recommended floodplain Manning's 'n'. Table 4.3 summarises the design values selected. Sensitivity tests on Manning's 'n' values are discussed in Section 5.2.3.

Table 4.3: Floodplain Roughness Values

Surface	Manning's 'n' Roughness Value
Standing water	0.040 to 0.050
River Banks - Dense Vegetation	0.075 to 0.085
Buildings	0.200
Roads and Hard Standing	0.030
Pasture, Parklands and Gardens	0.060

4.5 Model Run Parameters

The design models were run for the full inflow hydrograph duration to consider attenuation and the recession of any flooding in each AFA.

Initial river flow and level conditions were derived at every river section along the entire modelled reach for the 1D model components to match the start of the hydrograph for the current scenario, as well as the mid-range and high-end future scenarios. The minimum flows used to derive the initial conditions and lower limit of model stability are stated for each model reach in the model proformas included in the Appendices.

A 1D timestep interval of ten seconds was applied to the UoM19 1D-only models which is appropriate to resolve the fluvial hydrograph whilst maintaining stability of the model.

A 1D timestep interval of one second was applied to the UoM19 1D-2D models to ensure stability along the steep tributaries and to be divisible into the 2D timestep. A 2D timestep of two seconds was applied to all models to be divisible by the 1D timestep and within the recommended a half to a quarter of the 2D cell size.

All other run parameters were set to default both in ISIS and TUFLOW.

In 1D ISIS only models, the river sections were extended as discussed in Section 4.2 to avoid "glass-walling" of water above the limit of the cross-section. Hence the height added to the maximum section elevation (Dflood) was set to the default value of 3m.

5 Calibration and Sensitivity Analysis

5.1 Calibration

Table 5.1 outlines the historic flood events selected for the calibration of the hydraulic models during the hydrological analysis. The selection of historic events was based on scoring the flow estimates, observed data and reliable flood history as set out in Guidance Note 23[4].

Table 5.1: Selection of Calibration Events

Event	Model	Source of Flooding	Likely Accuracy of Flow Estimate[1]	Likely Accuracy of Gauged Level Estimate	Known Hydraulic Conditions[2]	Likely Accuracy of Spot Levels[3]	Reliable Flood History[4]	Indicative Calibration Score	Calibration Approach
19/11/2009	Ballingeary (Ballingeary and Inchigeelagh AFAs)	Fluvial	1	0	2	2	3	8	Flow estimate subject to uncertainty without flow or level gauge data to verify rainfall-runoff parameters. Calibration of both hydrological runoff and hydraulic flood mechanisms.
19/11/2009	Castlemartyr	Fluvial	1	0	2	2	2	7	Flow estimate subject to uncertainty without flow or level gauge data to verify transfer from neighbouring catchment.

Note 1: 3 = gauged flows are available in the catchment, 2 = gauged flows used from pivotal gauges nearby, 1 = rainfall data used to estimate flows using rainfall-runoff methodology and 0= no flow estimate available
Note 2: Hydraulic conditions relate to controls on water levels during a flood e.g. level of blockage, wall collapse etc.
Note 3 Levels during a known flood event NOT at a gauged location that represents a true flood level rather than a localised issue.
Note 4: Any information that includes date/time, precise location and mechanism of flooding

Only the 19th November 2009 extreme fluvial event along the Upper Lee at Ballingeary, Inchigeelagh and in Castlemartyr had sufficient spot levels, reports of areas flooding and flood extents to undertake model calibration.

It was noted that there were also flood events on 4th February 2004, 27th October 2004 and 7th January 2005 which affected properties in Ballingeary and Lough Allua. Rainfall combined with raised Lough levels downstream to cause flooding to properties along the R584 on each occasion. No flood levels were available for these events to calibrate. However, these recurring flood reports have been used to verify the 20%AEP flood extent.

Extreme flood events also occurred across the rest of River Lee catchment in August 1986, November 2000, November 2002, December 2006, January 2010, June 2012 as well as March and July 2013.

[4] Jacobs, (January 2013) Guidance Note 23 Model Calibration. Version 1.

However, there are no reliable records of flooding at the Ballingeary, Castlemartyr or Killeagh for these events. Hence they have not been considered for calibration purposes.

5.1.1 Ballingeary, Inchigeelagh and Castlemartyr 19th November 2009

The flooding of November 2009 was attributed to the heavy rainfall that fell in the preceding weeks and particularly due to torrential rainfall that fell overnight in the Upper Lee Catchment. Therefore, the catchment was saturated and levels in Lough Allua were already elevated before the 19th November 2009.

Flooding occurred at 17:30 due to overtopping on the Bunsheelin River at the eastern end of the village flooding properties by the Post Office due to high levels in Lough Allua. Overall, 19 residential properties were affected, plus the local school and six commercial properties. A 340m length of the R584 was also reported to be flooded. Residential and commercial losses were estimated at €300,000 and €750,000 respectively (*Meitheal Forbartha na Gaeltachta*, 2009)[5].

At Castlemartyr, flood waters spilled out-of-bank upstream of the Main Street Bridge to flood properties on the left bank. The flood waters then entered the sink-hole behind the houses which is suspected to add to flooding along the Lower Dower in the neighbouring catchment. The R632 road was flooded and three residential properties were affected.

The quality of the historic flood data from the post flood report has been reviewed:

- Photographs
  - The photographs were taken in Ballingeary during the event and the information has been converted to spot levels as described below.
  - All photographs with a visible flood level at an identifiable feature e.g. a brick wall were converted.
  - It was not possible to convert photographs of flooded fields to spot levels which did not have an identifiable feature to reference the level against.
  - However these photographs have been used to verify the flood outline provided.
  - Please see Map 5.1 for these observed levels listed in the table.
- Converted Spot Levels
  - Peak water levels recorded in photographs were converted to spot levels after the event by comparing the observed level in photograph with an identifiable feature e.g. a brick wall or the base of a road sign.
  - The depth of flooding in the photograph was then estimated from the number of bricks flooded and/or through interviews with the residents and reported depths
  - The ground level was extracted from the LiDAR DTM at the photograph locations and added to the depth of flooding to derive the flood level.
  - These levels are deemed to be reliable as they were observed during and after the event, but it is noted that the wrack marks could be influenced by local wash (natural or traffic) or capillary action on plaster walls. Therefore, the levels are deemed accurate to within 0.1m.
- Ballingeary Extent
  - It is not entirely clear how the flood outline was identified in Ballingeary but it is assumed that it was drawn from a combination of site observations, the photographs, flood levels and experience of the local residents.

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[5] Meitheal Forbartha na Gaeltachta (2009) Report on Ballingeary Flood, 19th November 2009.

  - The Ballingeary extent includes areas of high ground within the recorded extent which are some 4-5m above the recorded flood level. Therefore, these high areas within the recorded extent have been discounted.
  - However, the rest of the flood extent was intersected with DTM and found to be consistent with the recorded flood levels in the flood reports.
- Inchigeelagh Extent
  - It is not entirely clear how the flood outline was identified in Inchigeelagh but it is assumed that it was drawn from a combination of site observations and flood levels.
  - The digitised extent does not extend beyond the centre of Inchigeelagh. However due to the lack of flood reports in these reaches it has been assumed that there was flooding upstream and downstream but that it did not affect properties.
- Castlemartyr
  - The flooded areas were identified through an interview with the local area engineer and properties reported flooded on floodmaps.ie.

The design hydraulic models were modified as follows to represent the hydrological and hydraulic conditions of this event:

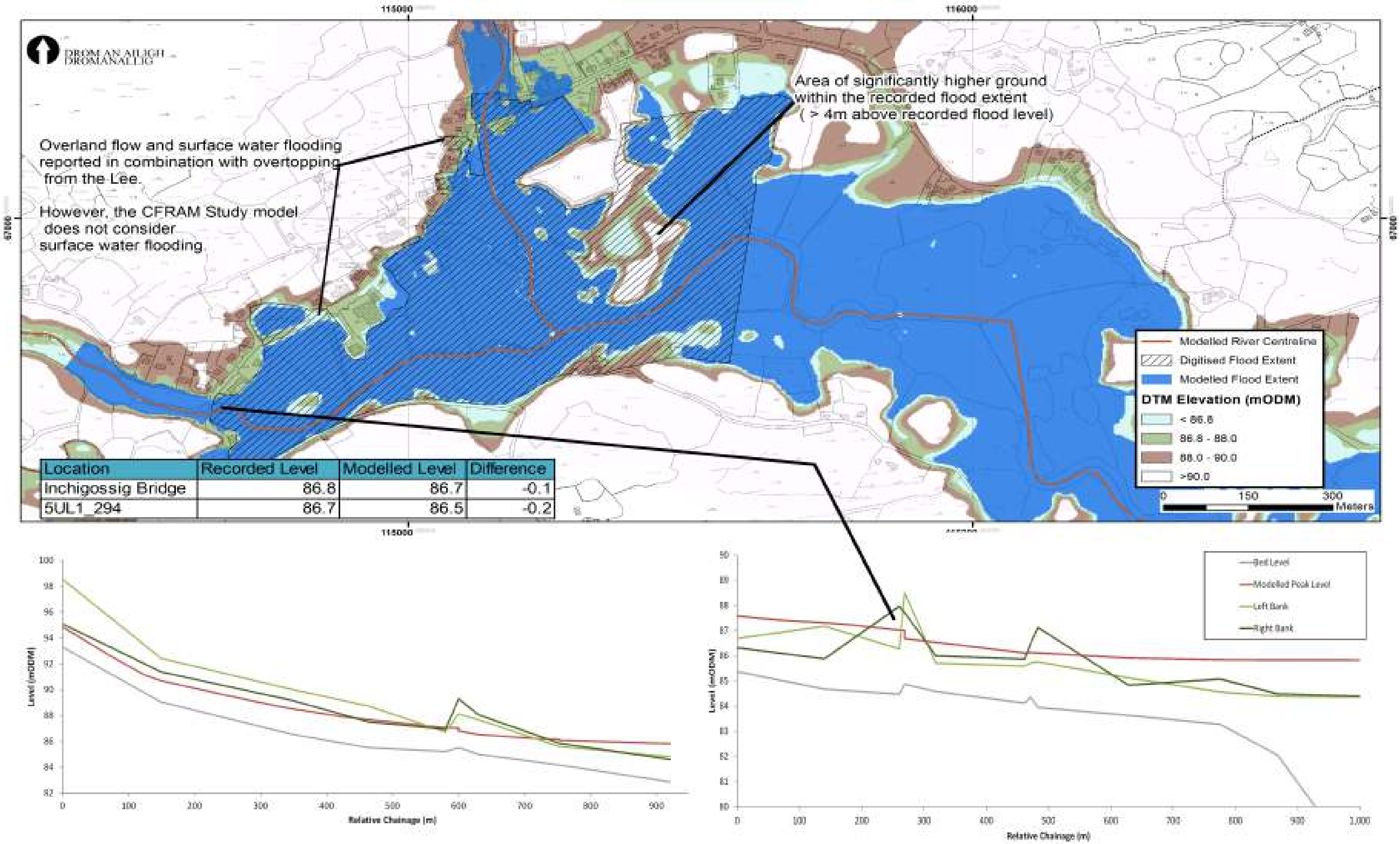
- Ballingeary and Inchigeelagh: The rainfall profile was transferred from Cork Airport and hydrographs produced using the FSSR16 rainfall-runoff approach with percentage runoff increased to 93% to represent the saturated conditions indicated in the Met Eireann observed SMD measurements, and phased to meet the target levels at Inchigossig and Inchigeelagh Bridges.
- Castlemartyr: The rainfall profile was transferred from Cork Airport and hydrographs produced using the FSSR16 rainfall-runoff approach with percentage runoff increased to 39% to meet record flows at Ballyedmond gauge in a neighbouring catchment. The rainfall-runoff parameters were then transferred to Castlemartyr to generate the inflows for this event.
- The sink holes in Castlemartyr were assumed to be saturated based on Met Eireann' s SMD observations at Cork Airport and as a conservative estimate of flood risk in Castlemartyr.

The hydraulic parameters were adjusted to best match the flood levels and extents, including:

- I18BY Ballingeary-Inchigeelagh model
  - The spill coefficient representing the bed drop through Inchigeelagh Bridge was lowered from 1.7 to 0.9 to represent the additional inefficiencies flow through the bridge and around the piers
  - In-channel Manning's 'n' values were increased from 0.04 to 0.06 for key cross-sections along the Bunsheelin River in Ballingeary to simulate the increased roughness from the in-channel bars surveyed and observed.
- I19CR Castlemartyr model
  - In-channel Manning's 'n' values were increased from 0.040 to 0.045 upstream of the Enterprise Centre
  - The spill coefficient at the River Kiltha and Golf Course Lake junction upstream was refined from 1.3 to 1.0 to represent the inefficiencies of flow over the vegetated bank.

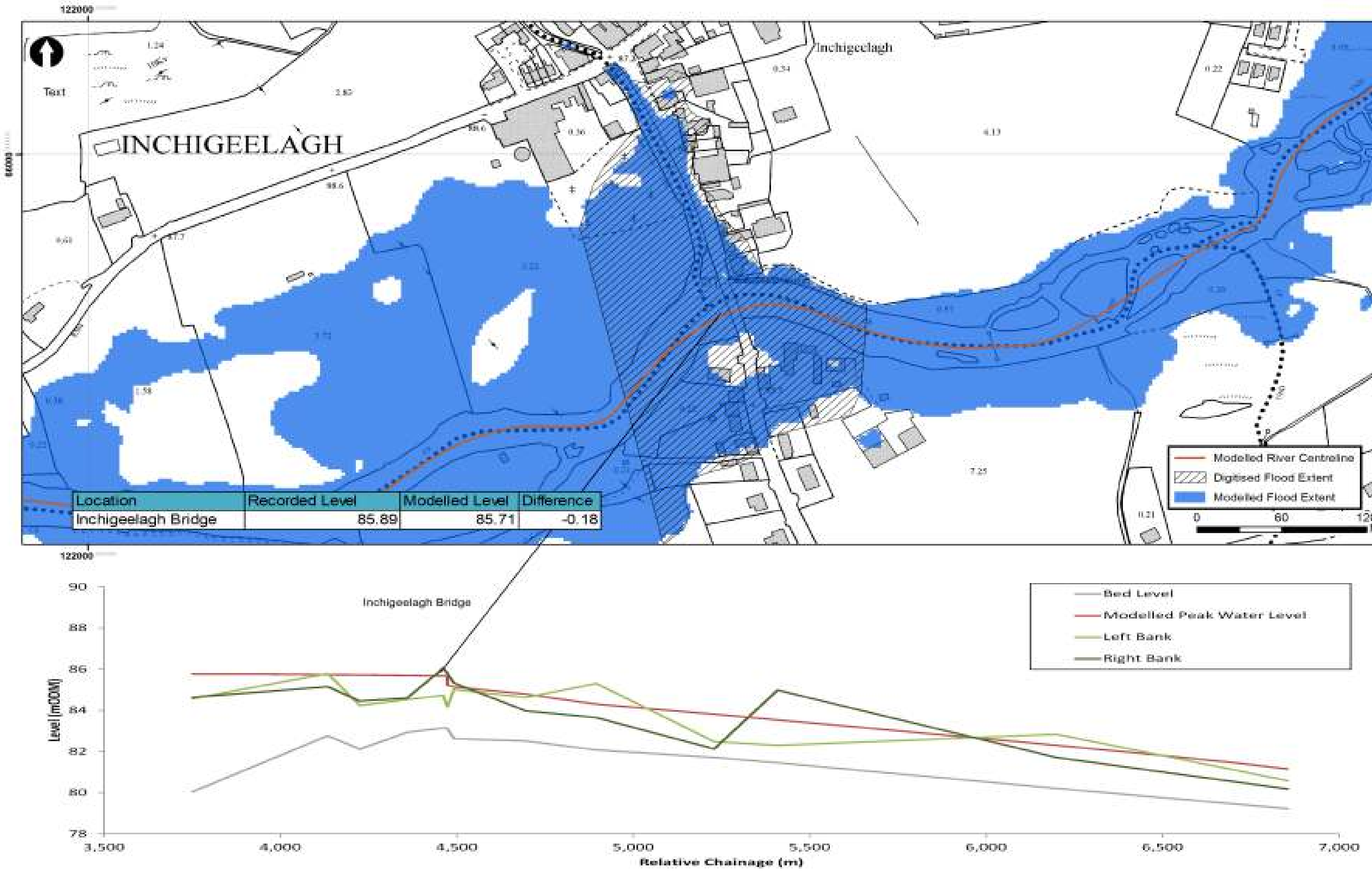
The Manning's 'n' values, the Inchigeelagh Bridge coefficient and the spill coefficients for the weirs under bridges representing the natural bed drop were adjusted to meet the recorded water levels upstream of the bridge and match the observed flood extent. Maps 5.1, 5.2 and 5.3 compare the resultant model extent and levels with the recorded information.

Map 5.1: Calibration of the Ballingeary Model in Ballingeary to the 19 November 2009 Event



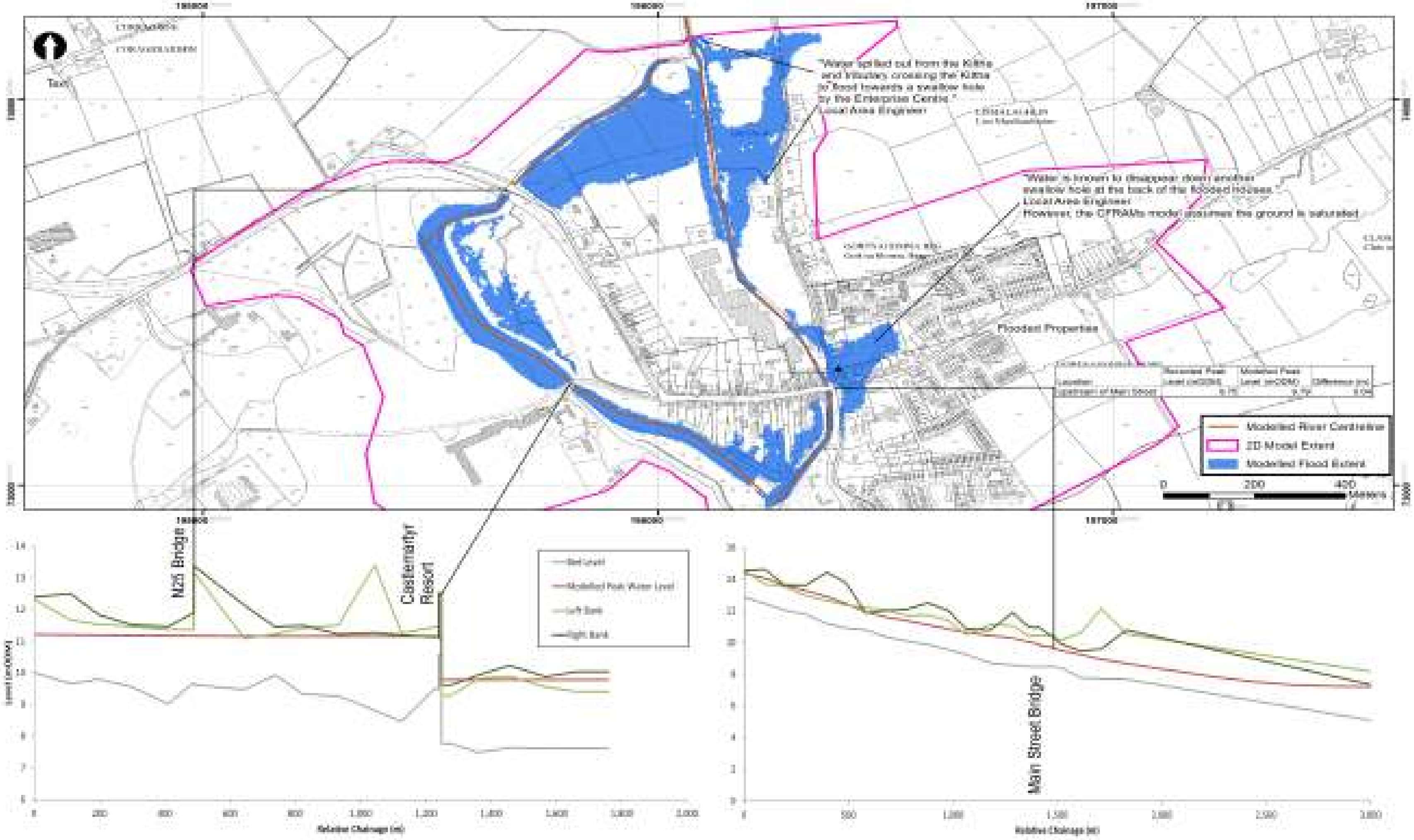
Location	Recorded Level	Modelled Level	Difference
Inchigossig Bridge	86.8	86.7	-0.1
5UL1_294	86.7	86.5	-0.2

Map 5.2: Calibration of the Ballingeary Model in Inchigeelagh to the 19 November 2009 Event



Mott MacDonald

Map 5.3: Calibration of the Castlemartyr Model to the 19 November 2009 Event



Overall, the calibrated model results match well with the historic flood evidence. The calibration for each AFA is described below.

Ballingeary

The modelled peak water level was within 0.1m of the recorded flooding at Inchigossig Bridge and 0.2m on Bunsheelin Stream by the Post Office. However the flood extent and depths matched well at the Garda Station, Post Office and towards Parochial House and Casadh Spride Park. The model predicted slightly less flooding upslope of the Church, which was caused partly by surface water flowing down the steep valley sides. This overland flow has not been considered in the CFRAM model.

Inchigeelagh

The model predicted water backing-up from Inchigeelagh Bridge to overtop the road and flood properties. This is consistent with the OPW flood report. The flood level upstream of the bridge was within 0.2m of the recorded peak level. However the extent and depth of flooding at properties is consistent with the flood report. Therefore, the model calibrated well with the mechanisms and extent of flooding recorded in November 2009.

Castlemartyr

The model was calibrated to reproduce the extent of flooding and flow paths at the Grange and flooding of properties upstream of the Bridge. The flood level was within 0.05m of the recorded peak level but the flood extent was larger than recorded behind the houses. However, the local engineer noted that water disappeared down a sink hole behind the houses whereas the CFRAM model assumes this sink hole to be saturated as a conservative estimate of flood risk to Castlemartyr.

5.1.2 Summary

Table 5.3 summarises the calibration run performance, average difference from recorded levels, and tolerance of recorded levels for the November 2009 event. The average error of the modelled flood levels were within the confidence limit of the recorded levels for the calibration events.

Table 5.2: Summary of Calibration Performance

Event	Reliability of Recorded Level	Location	Absolute Difference to Recorded Level/Depth (m)	Root Mean Square Difference
19 November 2009	±0.25m. Due to transfer of flood depths to spot level	Ballingeary AFA	-0.20	0.10
	±0.25m. Due to transfer of flood depths to spot level	Inchigeelagh AFA	-0.18	0.18
	±0.25m. Due to transfer of flood depths to spot level	Castlemartyr AFA	0.04	0.04

The model predicted levels are within the confidence limit of the recorded levels at all the AFAs and match well with the mechanisms and flood extents in general.

Flood risk was slightly underestimated along the road at Casadh Spride Park and upstream of the Church in Ballingeary because the CFRAM design model does not consider flooding from pluvial sources.

Flood risk was slightly overestimated in Castlemartyr behind the houses on Mogeely Road and by the Enterprise Park because the sink holes were assumed to be saturated as a conservative estimate of flood risk in the AFA.

5.2 Sensitivity Analysis

5.2.1 Flow

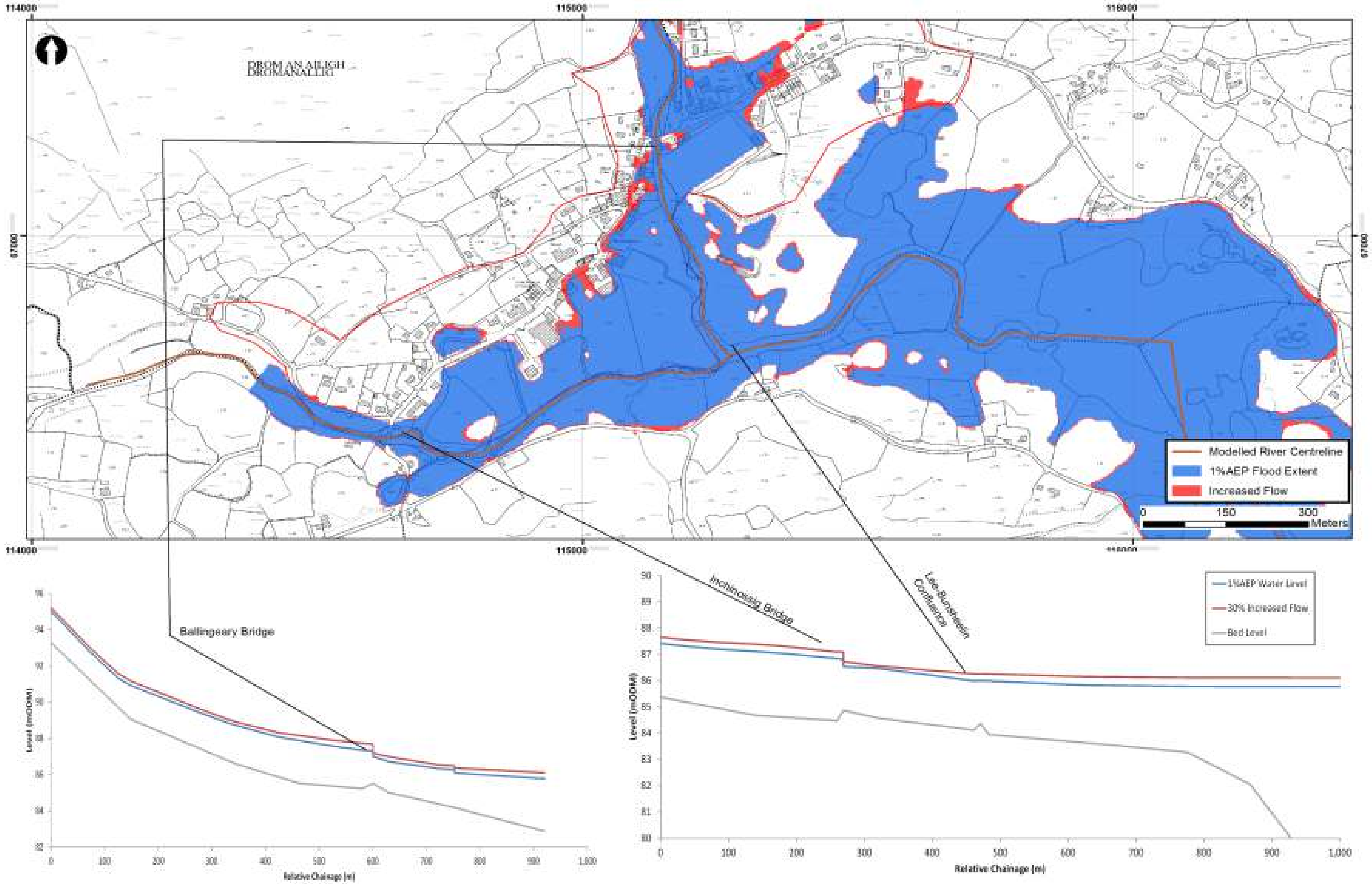
In accordance with CFRAM Guidance Note 22, the 1%AEP design peak flow was increased by 30% to assess the sensitivity to uncertainties in the $QMED_{rural}$ coefficients, the selection of pivotal sites and the flood growth curves derived in the hydrological analysis. This is approximately equivalent to the flow increase applied to simulate climate change in the High End Future Scenario (HEFS), as the increase in flows due to urbanisation is less than 1%.

In UoM19, Ballingeary (Map 5.3) and Inchigeelagh (Map 5.4) were the most sensitive to assumptions in peak flow because flooding is associated with the volume available in Lough Allua and the capacity of Inchigeelagh Bridge at the outfall. The increased flows fill Lough Allua causing greater backwater to Ballingeary and greater overtopping at Inchigeelagh.

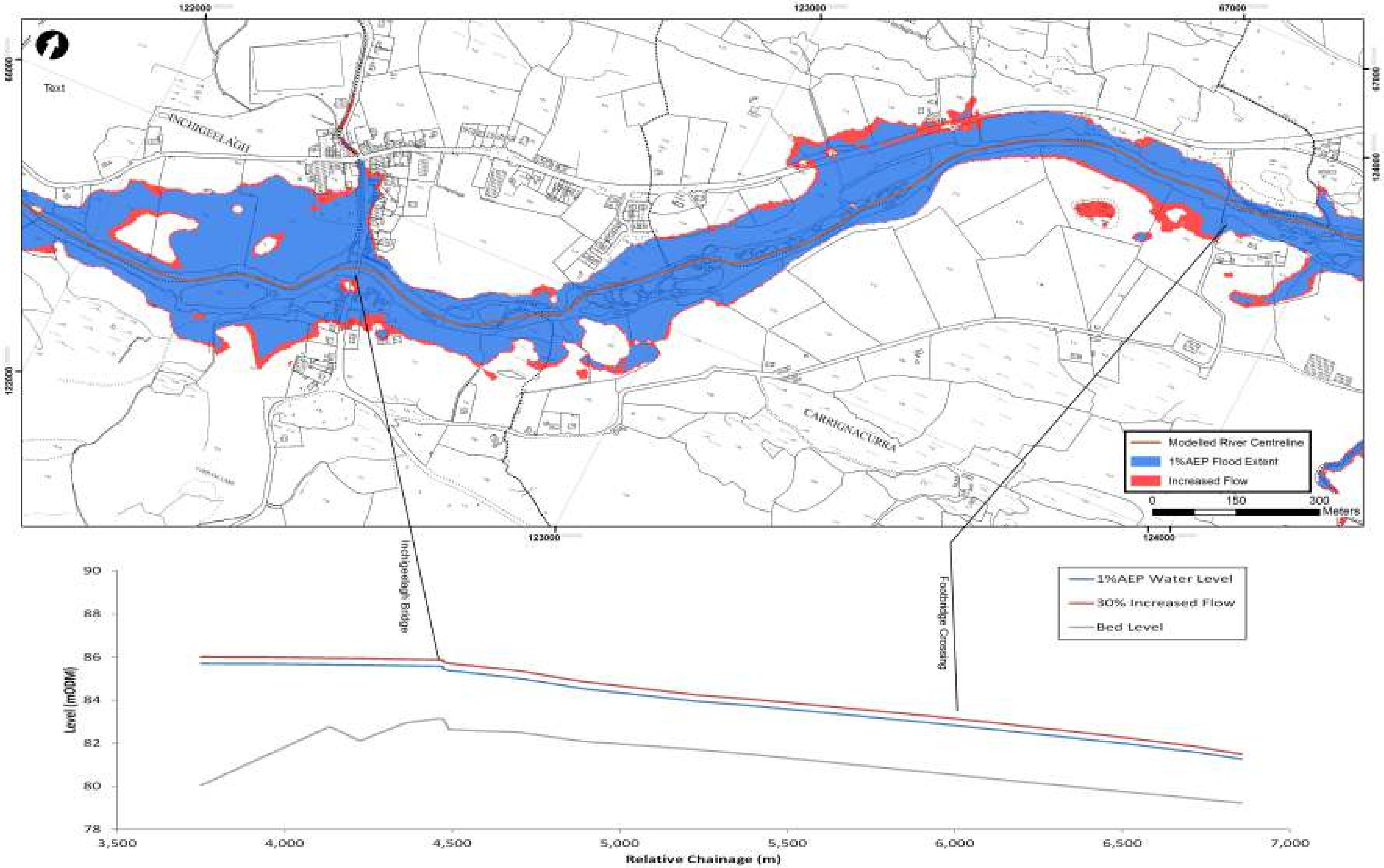
Castlemartyr, Killeagh and the Womanagh MPW all experienced increased levels and small increases in flooding with the increased flows, but this does not affect properties in the AFAs.

The plots for all flow sensitivity tests can be found in the model performance proformas in the relevant Appendices.

Map 5.4: Sensitivity to Peak Flow – Ballingeary



Map 5.5: Sensitivity to Peak Flow-Inchigeelagh



5.2.2 Level

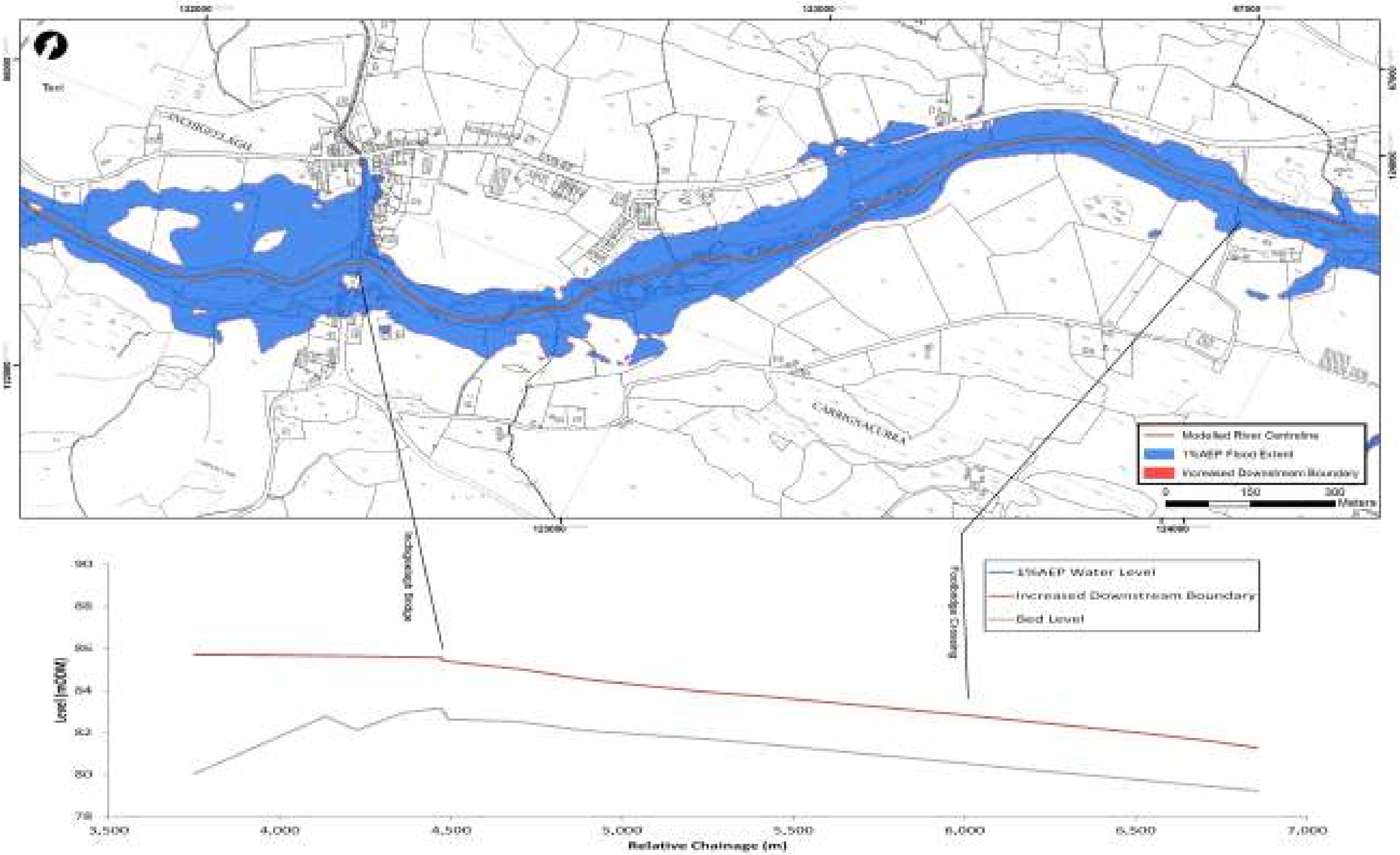
A sensitivity test was undertaken on downstream water level for the tidally-affected Womanagh model in UoM19. This was done to investigate the uncertainties in the estimation of extreme tide plus surge levels extracted from the ICPSS model, and the uncertainties in the transformation of water levels along the various bays. The downstream water level was increased by 0.5m to account for these uncertainties. This is broadly equivalent to the sea level increase applied to simulate climate change in the Mid-Range Future Scenario (MRFS). Flood extent and risk were sensitive to the downstream tidal conditions downstream of Old Finisk Bridge as this overtopped a greater length of the raised embankments to flood the low lying coastal floodplain.

For fluvial dominated models, a sensitivity test was undertaken to assess the sensitivity to the downstream boundary assumptions on flood risk in the AFA. The downstream boundary gradient was flattened by 25%, or a feasible increase in water slope based on the downstream model.

In UoM19,the flatter downstream boundary increased flood level by a maximum of 0.07m and did not significantly increase flood risk within the AFAs because the downstream boundaries were located sufficiently downstream or below a hydraulic structure to limit any influence in the AFA (example of Inchigeelagh Map 5.6). Therefore, none of the fluvial dominated models were deemed to be sensitive to the downstream boundary assumptions.

The plots for all level sensitivity tests can be found in the model performance proformas in the relevant Appendices.

Map 5.6: Sensitivity to Downstream Level – Inchigeelagh



5.2.3 Roughness

In accordance with CFRAM Guidance Note 22, the Manning's 'n' was increased to the next highest value in the recommended ranges for that channel or surface type (Chow 1959) in both the 1D and 2D model components. The Manning's 'n' values were increased in the design model as specified in Table 5.3 and the 1%AEP fluvial event simulated to assess the sensitivity of the predicted flood outline to assumptions in roughness.

Table 5.3: Sensitivity Manning's 'n' Values

Channel or Surface	Design Manning's 'n'	Sensitivity Manning's 'n'
Active River Channel in Inchigeelagh	0.045- 0.050	0.050-0.055
Active River Channel in the Upper Lee, Kiltha , Dissour and Womanagh	0.040	0.045
River Banks/ Medium to Dense Vegetation	0.085	0.100
Buildings	0.200	0.300
Roads and Other Hard Standing	0.033	0.040
Rural/Pasture	0.060	0.080

In UoM19, an increase in Manning's 'n' caused water levels to rise by a maximum of 0.1 but this did not cause additional flooding of properties in the 1%AEP fluvial current event. The greatest increase in flood risk attributed to Manning's 'n was predicted downstream of Inchigeelagh Bridge due to the reduced capacity of the channel through the island reach (Map 5.7) upstream of School Road. However, the typical increase in water level was less than 0.13m and did not increase flooding to any properties, roads or environmentally-protected features.

The plots for all Manning's 'n' sensitivity tests can be found in the model performance proformas in the relevant Appendices. Table 5.5 summarises the impact on flood levels.

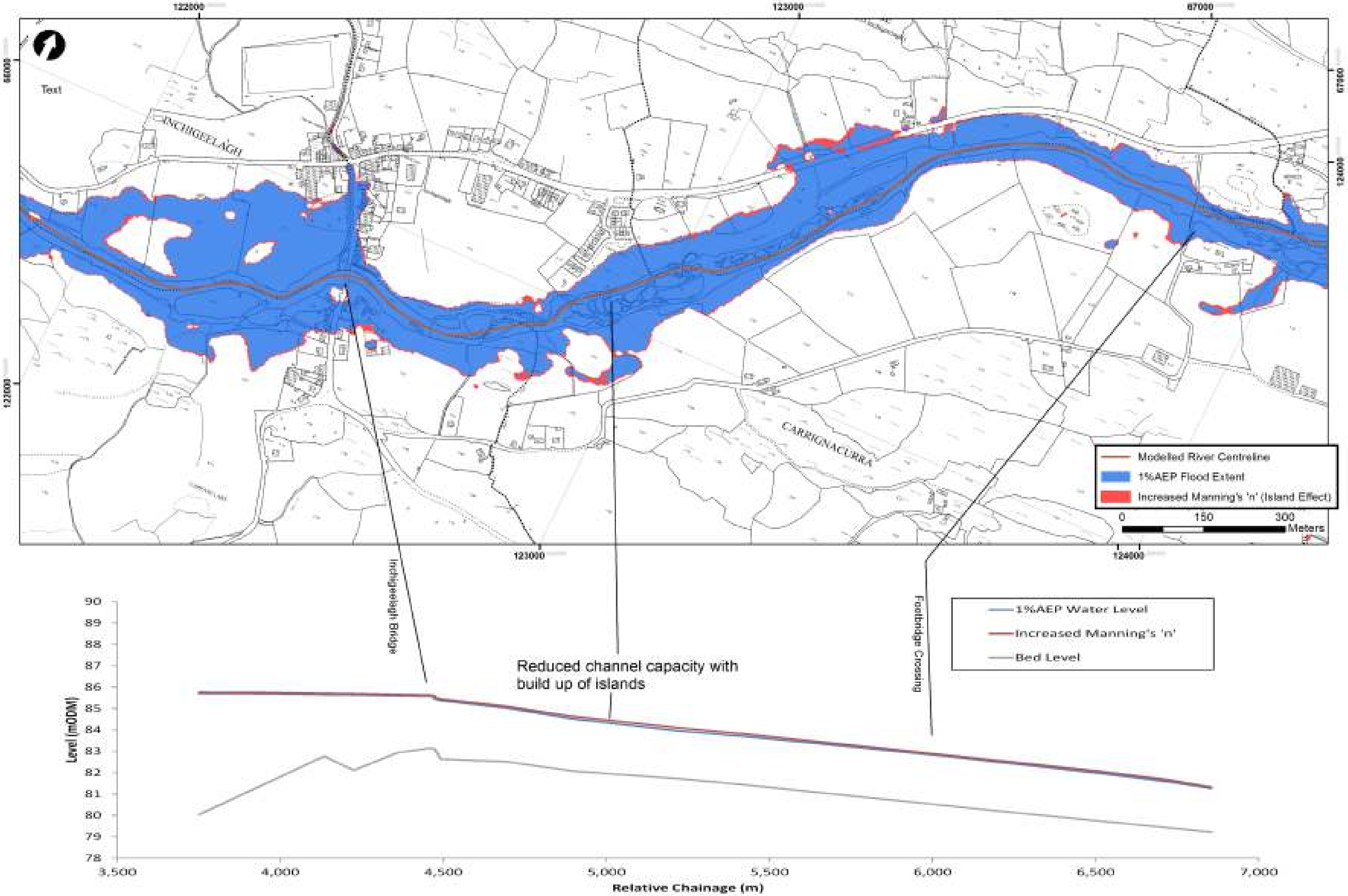
5.2.4 Flood Hydrograph Duration

Flood risk in Ballingeary and Inchigeelagh is driven by consecutive storm events such as November 2009 rather than the single peak event assumed in industry standard rainfall runoff methods. The design hydrograph assumed a longer duration event to simulate the effective volume that causes Lough Allua to fill and flood the AFAs as a conservative estimate. However, a test has been undertaken on the single peak event to assess the sensitivity of flood risk to the storm duration as a proxy for flood hydrograph volume. Therefore, the storm duration was reduced from 43 hours to 11 hours (the critical duration used in the Lee CFRAMS) in the Ballingeary model (Maps 5.8 and 5.9).

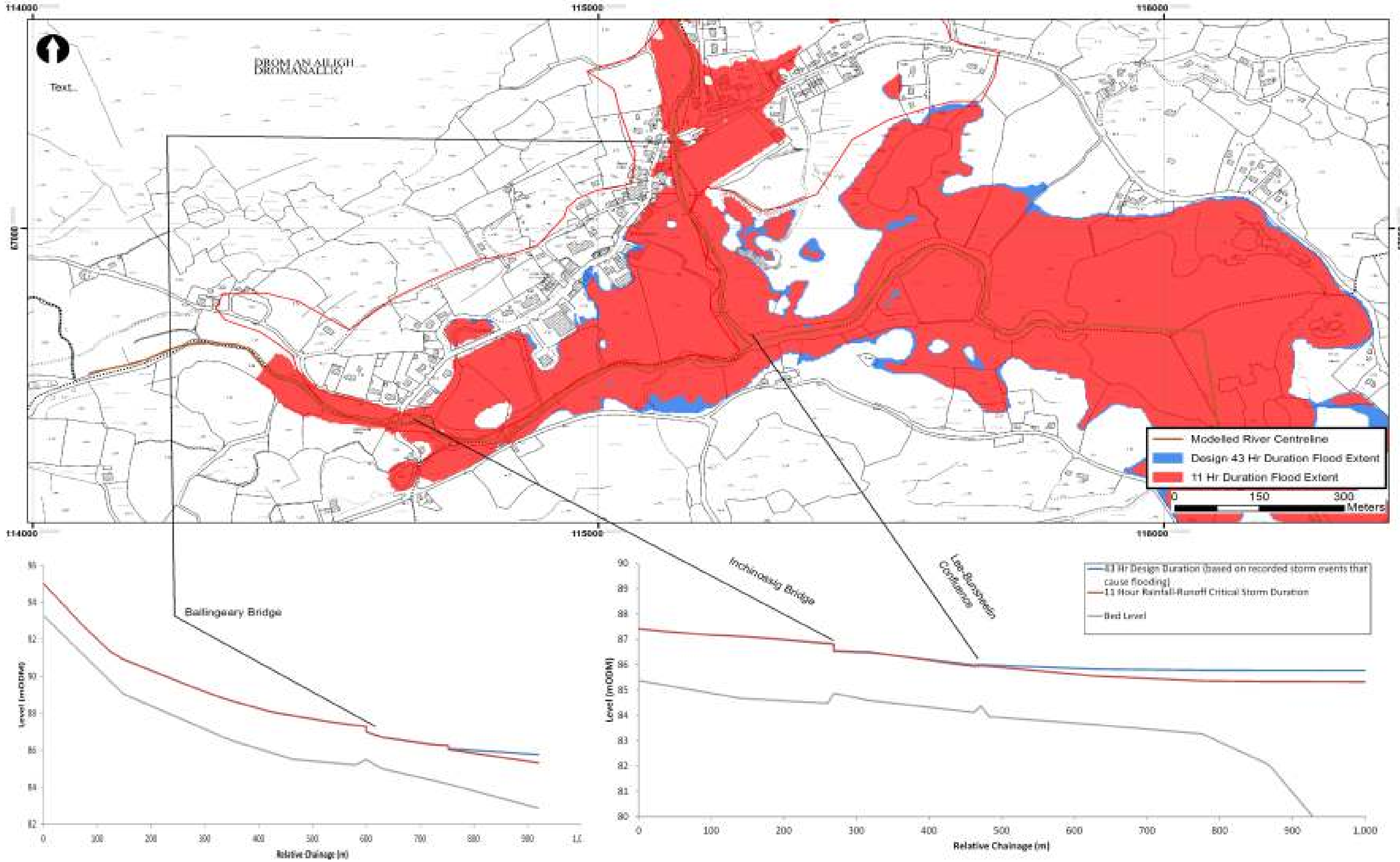
The shorter duration resulted in a 0.44m drop in peak water level along through Lough Allua because the shorter duration storm/single peak event has significant less volume to fill the Lough. Therefore, there is not as much backwater upstream of Inchigeelagh Bridge to flood Ballingeary and the water level does not rise enough to overtop the road at Inchigeelagh.

Whilst specific sensitivity tests were not carried out in respect of storm duration for Castlemartyr, Killeagh and the Womanagh, the impact of the increased volume has been investigated through the analysis of increased peak flows which simulates a similar increase in volume. The impacts of the increase storm duration would be similar to the impacts arising from the increase in peak flow.

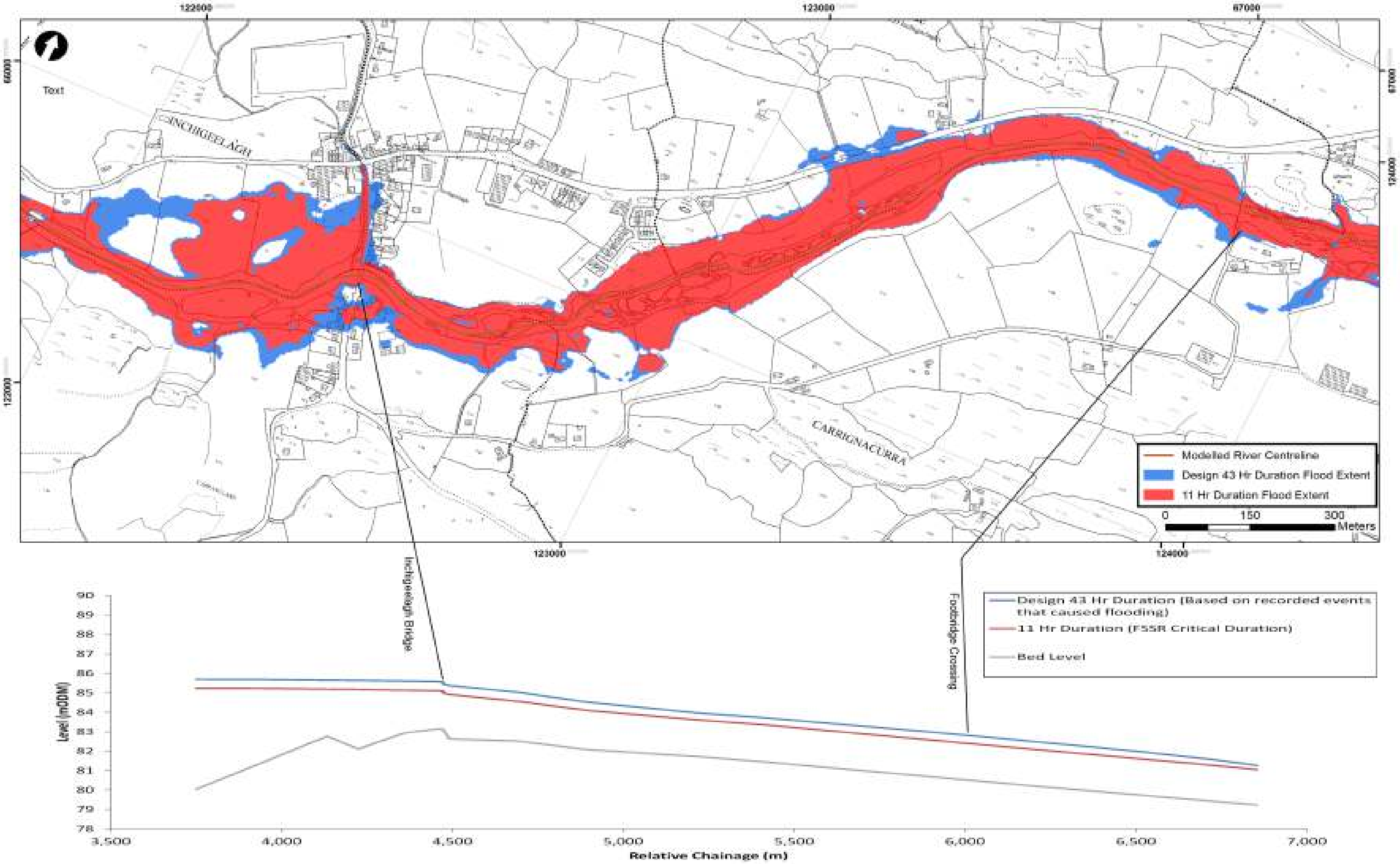
Map 5.7: Sensitivity to Manning's 'n' – Inchigeelagh Model



Map 5.8: Sensitivity to Flood Hydrograph Duration – Ballingeary



Map 5.9: Sensitivity to Flood Hydrograph Duration – Inchigeelagh



5.2.5 Summary

Table 5.4 summarises the findings of the sensitivity tests undertaken on the design models. Each was deemed sensitive to a parameter if there was a significant increase in flooded area, as well as an increase in flood risk to properties.

Table 5.4: Summary of Sensitivity Run Performance

Model/AFA	Peak Flow		Level		Manning's 'n'		Storm Duration	
	RMSD (m)	Sensitive?	RMSD (m)	Sensitive?	RMSD (m)	Sensitive?	RMSD (m)	Sensitive?
Ballingeary at Ballingeary AFA	0.36	Yes	0.00	No	0.10	No	0.36	Yes
Ballingeary at Inchigeelagh	0.33	Yes	0.00	No	0.09	No	0.44	Yes
Castlemartyr	0.20	No	0.07	No	0.14	No	N/A	
Killeagh	0.14	No	0.07	No	0.10	No	N/A	
Womanagh	0.20	No	0.55*	Yes	0.14	No	N/A	

RMSD is Root Mean Square Difference.
*RMSD for open coast is the absolute increase in water level i.e. 0.55m.

Based on the findings of the sensitivity tests above, the following can be concluded:

- Flood risk in Ballingeary and Inchigeelagh is sensitive to both uncertainties in peak flow and particularly sensitive to the uncertainties of storm duration .These parameters determine the flood volume to fill Lough Allua and cause flooding in both these AFAs.
- Flood risk in Castlemartyr and Killeagh were not found to be sensitive to uncertainties in flow, assumptions in the downstream boundary or Manning's 'n' at the 1%AEP.
- Flood risk along the lower Womanagh is sensitive to uncertainties in the total tide plus surge level because large areas of low-lying land quickly become inundated once the River Womanagh overtops the raised tidal embankments.
- Flood risk to property in all the fluvial-dominated models were not found to be sensitive to the downstream boundary assumptions
- None of the UoM19 models were found to be sensitive to Manning's 'n' at the 1%AEP event because the 1%AEP event already floods the majority of the floodplains and the small increase in levels did not cause a significant increase in flooding to properties.

6 Design Event Runs and Model Performance

6.1 Design Scenarios and Event Runs

Table 6.1 outlines the applicable design scenarios to each model in UoM19 and the design event runs simulated.

Both the fluvial and coastal scenarios have been simulated for the Womanagh MPW as this reach has been identified as being at risk from both fluvial and coastal sources. The joint probability between the fluvial and coastal conditions for these scenarios is outlined in Section 3.3 of this report.

No coastal scenarios have been simulated for any of the AFAs because the rivers at Castlemartyr, Killeagh, Ballingeary and Inchigeelagh are not tidally influenced.

No wave overtopping scenarios have been simulated in UoM19 because no areas have identified as vulnerable to wave overtopping by the ICWWS.

Table 6.1: Design Event Runs

Source	Scenario	%AEP	Run Name	Ballingeary and Inchigeelagh Model (I18BY)	Castlemartyr Model (I19CR)	Killeagh Model (I20KL)	Womanagh Model (I21WH)
Fluvial	Current	50%	FCD500_D1	✓	✓	✓	✓
		20%	FCD200_D1	✓	✓	✓	✓
		10%	FCD100_D1	✓	✓	✓	✓
		5%	FCD050_D1	✓	✓	✓	✓
		2%	FCD020_D1	✓	✓	✓	✓
		1%	FCD010_D1	✓	✓	✓	✓
		0.50%	FCD005_D1	✓	✓	✓	✓
		0.10%	FCD001_D1	✓	✓	✓	✓
	MRFS	50%	FMD500_D1	✓	✓	✓	✓
		20%	FMD200_D1	✓	✓	✓	✓
		10%	FMD100_D1	✓	✓	✓	✓
		5%	FMD050_D1	✓	✓	✓	✓
		2%	FMD020_D1	✓	✓	✓	✓
		1%	FMD010_D1	✓	✓	✓	✓
		0.50%	FMD005_D1	✓	✓	✓	✓
		0.10%	FMD001_D1	✓	✓	✓	✓
	HEFS	10%	FHD100_D1	✓	✓	✓	✓
		1%	FHD010_D1	✓	✓	✓	✓
		0.10%	FHD001_D1	✓	✓	✓	✓
Coastal	Current	50%	CCD500_D1	N/A	N/A	N/A	✓
		20%	CCD200_D1	N/A	N/A	N/A	✓
		10%	CCD100_D1	N/A	N/A	N/A	✓
		5%	CCD050_D1	N/A	N/A	N/A	✓
		2%	CCD020_D1	N/A	N/A	N/A	✓
		1%	CCD010_D1	N/A	N/A	N/A	✓
		0.50%	CCD005_D1	N/A	N/A	N/A	✓

Source	Scenario	%AEP	Run Name	Ballingeary and Inchigeelagh Model (I18BY)	Castlemartyr Model (I19CR)	Killeagh Model (I20KL)	Womanagh Model (I21WH)
		0.10%	CCD001_D1	N/A	N/A	N/A	✓
	MRFS	50%	CMD500_D1	N/A	N/A	N/A	✓
		20%	CMD200_D1	N/A	N/A	N/A	✓
		10%	CMD100_D1	N/A	N/A	N/A	✓
		5%	CMD050_D1	N/A	N/A	N/A	✓
		2%	CMD020_D1	N/A	N/A	N/A	✓
		1%	CMD010_D1	N/A	N/A	N/A	✓
		0.50%	CMD005_D1	N/A	N/A	N/A	✓
		0.10%	CMD001_D1	N/A	N/A	N/A	✓
	HEFS	10%	CHD100_D1	N/A	N/A	N/A	✓
		0.50%	CHD005_D1	N/A	N/A	N/A	✓
		0.10%	CHD001_D1	N/A	N/A	N/A	✓
TOTAL Model Runs				19	19	19	38

6.2 Model Run Performance

The run performance was investigated for each of the design models. Figures 6.1 to 6.4 show the performance dialog for the 0.1%AEP fluvial event for the following run performance criteria in the 1D model components;

- The number of iterations per timestep taken to resolve flow and level in the model;
- The convergence of flow and water level in the model within the recommended tolerance of +/- 0.01 m or 0.01 m^3/s between consecutive timesteps;
- The total inflow and outflow from the model components.

The 1D ISIS models were convergent within the recommended tolerances for the majority of the design event in all models. The following observations can be made:

- The initial poor convergence in all models is associated with using average initial conditions as a common starting place for all scenarios. However this quickly stabilises within recommended tolerances within 0.25 hours and does not affect the peak.
- The spikes in poor convergence at 0.5 and 12 hours in the Womanagh model are attributed to rapid flow through the narrow opening in the spill into the set-back area downstream of Crompaun Bridge (530L reservoir) at the changing of the tide during low fluvial flow. However, this occurs before the peak flood and does not affect peak level.

The cumulative mass balance for the 2D model components is shown in Figures 6.5 and 6.6. All the design models were convergent and within the recommended tolerance of ±1% mass error at the peak flow and/or tide plus surge level. There is an initial increase in cumulative mass error for when water spills out–of-bank in both the Castlemartyr and Killeagh models caused by the wetting of the cells. However, the mass error rapidly decreases to less than 0.5% and does not affect the model results at the peak flow.

Figure 6.1: 1D Convergence Plot – Ballingeary and Inchigeelagh

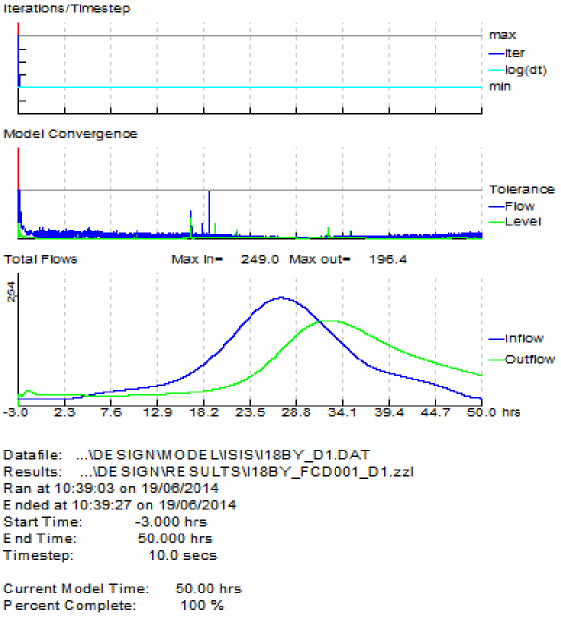


Figure 6.2: 1D Convergence Plot - Castlemartyr

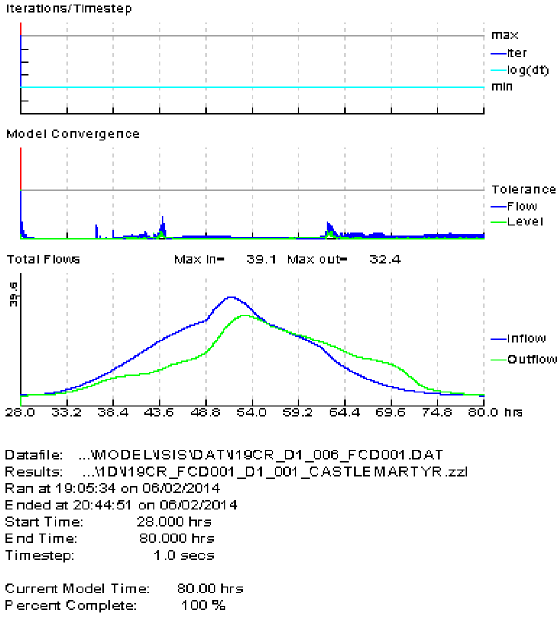


Figure 6.3: 1D Convergence Plot – Killeagh

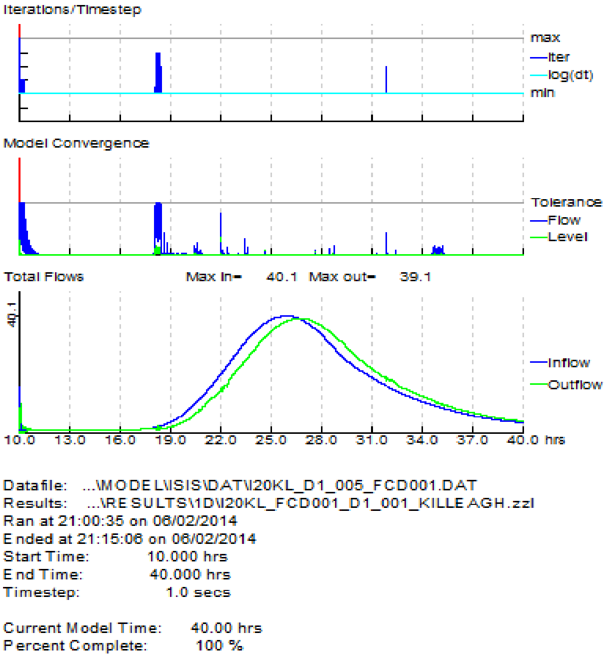


Figure 6.4: 1D Convergence Plot - Womanagh

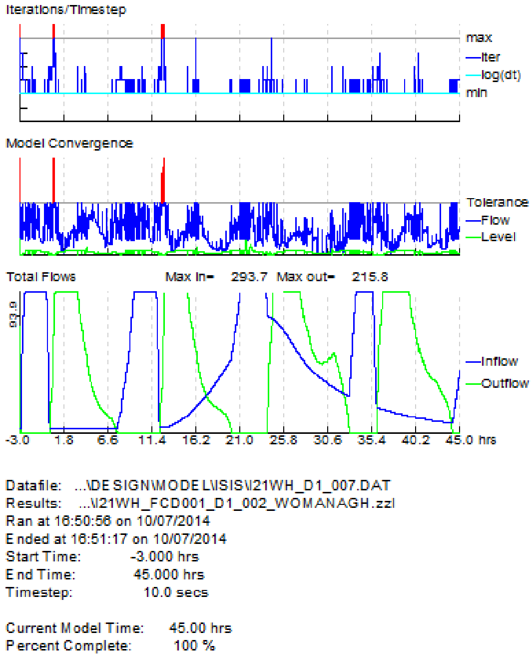


Figure 6.5: 2D Mass Balance Plot - Castlemartyr

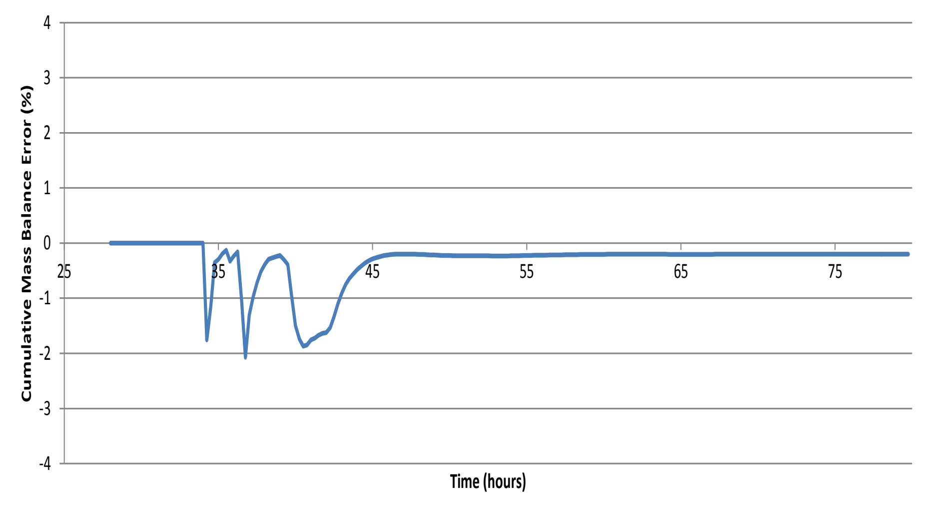
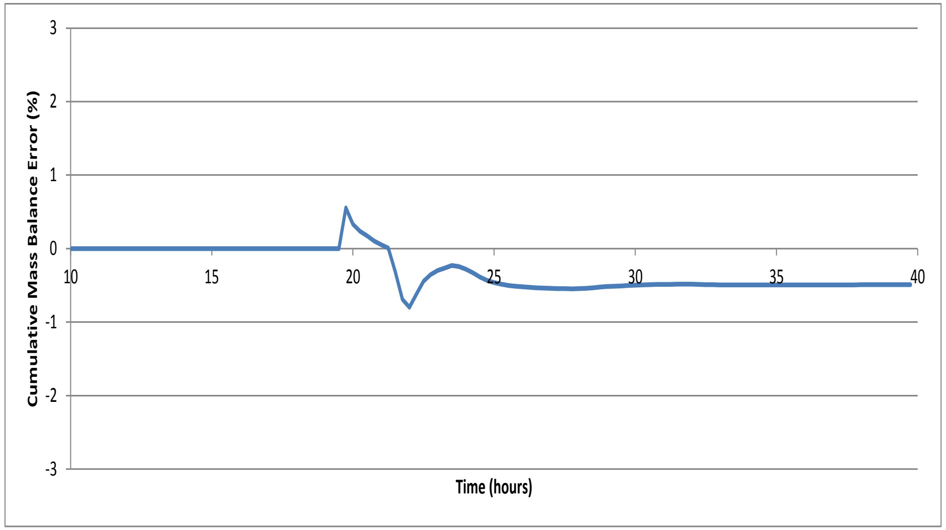


Figure 6.6: 2D Mass Balance Plot - Killeagh



Tables 6.2 compares the model predicted flows with the design peak flows at the target HEPs for the target 1%AEP event. The model predicted flows have been derived by combining the flows in the 1D channel and across the 2D floodplain to assess the hydrological routing of flows through the catchment. Target flows at HEPs located upstream of confluences were not assessed because these locations are affected by backwater which is not considered in the design hydrology.

Table 6.2: Summary of Hydrological Routing Performance for the 1%AEP Fluvial Current Event

HEP ID	Location	Model Node	10%AEP			1%AEP			0.1%AEP		
			Design Target Flow (m3/s)	Model Predicted Flow	Difference (m3/s)	Design Target Flow (m3/s)	Model Predicted Flow	Difference (m3/s)	Design Target Flow (m3/s)	Model Predicted Flow	Difference (m3/s)
Ballingeary											
19_927_2	d/s Bunsheelin	5UL1_167	34.2	34.1	0%	51.00	50.81	0%	76.0	75.8	0%
19_925_1	Downstream on Lee with Bunsheelin Confluence	5ULE_52298U	90.0	88.1	-2%	135.0	131.5	-3%	202.1	196.3	-3%
19_1714_2	Lee outfall into Lough Allua	5ULE_51483	102.1	89.1	-13%	154.1	133.4	-13%	231.6	200.7	-13%
Castlemartyr											
19_909_11	Upstream Boundary	19KILT00304H	10.20	10.21	0%	15.50	15.53	0%	23.50	23.45	0%
19_1909_15	Kiltha at Downstream of Golf Course Channel	19KILT00120E	12.40	10.94	-12%	18.86	16.95	-10%	28.49	24.80	-13%
19_1909_17	Kiltha at confluence with Womanagh	19KILT00041H	12.50	10.95	-12%	19.00	17.03	-10%	28.70	26.16	-9%
Killeagh											
19_686_10	Dissour u/s Survey Extent	19EAGH00379H	13.30	13.54	2%	19.60	19.91	2%	29.00	29.40	1%
19_686_15	Dissour d/s Survey Extent - Moanlahan Bridge	19EAGH00242A	13.60	13.53	-1%	20.00	19.88	-1%	29.50	28.85	-2%
19_1798_3	Dissour u/s Womanagh	19EAGH00002H	18.40	18.26	-1%	27.10	26.78	-1%	40.10	39.10	-2%
Womanagh											
19_705_1	River Womanagh Upstream	19WOMA01727H	16.7	16.67	0%	25.1	25.1	0%	37.7	37.8	0%
19_1823_1	Womanagh downstream Ladysbridge	19WOMA01658B	18.2	17.84	-2%	27.4	26.4	-4%	41.2	39.1	-5%
19_1833_1	Womanagh downstream Dower	19WOMA01502H	23	22.18	-4%	34.7	32.3	-7%	52.1	47.4	-9%
19_1793_1	Womanagh downstream Ballying	19WOMA01038H	27.4	23.71	-13%	41.3	33.9	-18%	62.1	49.4	-20%

HEP ID	Location	Model Node	10%AEP			1%AEP			0.1%AEP		
19_1794_1	Womanagh downstream Dissour (Finisk Bridge)	19WOMA00964B	43.9	33.53	-24%	66.1	46.2	-30%	99.3	66.5	-33%
19_1941_2+	River Womanagh (Crompaun Bridge)	19WOMA00534A	46.8	37.65	-20%	70.5	40.2	-43%	105.9	50.9	-52%

The modelled flows are within 10% of the design flows where the HEP is not bypassed or affected by backwater.

The discrepancy in flow on the Lee is generated by backwater along Lough Allua due to the limited discharge through Inchigeelagh Bridge and longer design flood hydrograph filling the lough (highlighted orange).

The discrepancy in flow at the Kiltha-Womanagh confluence (highlighted green) is generated by backwater from the larger River Womanagh downstream.

The discrepancies in flows at the tidal outfalls are due to the tidal influence limiting discharge (highlighted yellow). These backwater effects are not considered in the design hydrology which assumes free-flow conditions.

7 Assumptions and Limitations

7.1 Assumptions

A number of assumptions were made in the development of the hydraulic model and application of the hydrological inflows. They include:

- The lateral inflows representing the intermediate catchments were assumed to be distributed evenly, as rainfall across such a small catchment can be expected to be uniform.
- The peak fluvial flows were assumed to coincide with the peak tidal level on the Lower Womanagh as a conservative estimate of flood risk. However, it is recognised that the phasing of the river flows and tide will vary event to event.
- The urban drainage networks are assumed to be at capacity prior to the start of the event as the worst case scenario as observed in several historic flood events. Therefore, the urban drainage networks are not explicitly considered in the design models.
- Model grid size is set at 5 m which was assessed as appropriate for the purpose of the Study. Small urban features, such as fences and walls, have not been considered explicitly as they are not designed to retain water during a flood event. However, the overall impact of these features has been incorporated into the floodplain Manning's 'n'.
- Section data for the cross sections was defined with the hard bed levels. This is because the soft bed or silt is likely to be washed away during a flood.
- It is assumed that water can enter a building above a 0.15m threshold whereupon the water is significantly retarded by the internal structure before exiting the building.
- The "stubby" building approach described above can result in the model calculating reduced flood depths and velocities, along with a greater flood extent as flows are not constricted between buildings.
- A longer storm duration has been selected as the design flood event in the Ballingeary-Inchigeelagh model based on the rainfall profiles of events which are known to cause flooding in these AFAs.
- The swallow hole by the Enterprise Centre in Castlemartyr is assumed to be blocked and/or saturated to simulate a worst-case scenario for flood risk in the AFA.

7.2 Limitations

There are a number of uncertainties associated with the flow estimation and hydraulic modelling methodology used in UoM19. They include:

- The absence of river flow, spot gaugings and flood levels in Killeagh to fully calibrate the hydrological routing and hydraulic model.
- The flood maps produced as part of this Study do not show localised flooding resulting from intense rainfall and where surface flow might exceed the capacity of the urban drainage system. The assessment of such surface water flooding is beyond the scope of the CFRAM studies.
- Groundwater flooding has not been included in assessing the risk of flooding and therefore areas susceptible to groundwater flooding may not be identified in the flood maps as it is not part of the

CFRAM brief. However, groundwater is potential source of flooding in the karstic catchments of the Dower and Balling Streams. Groundwater may also exacerbate flooding in Castlemartyr. However a worst-case of full saturation has been assumed for the purpose of flood mapping.

8 Flood Mapping Approach

8.1 Approach

The 1D model and combined 1D and 2D results were used to produce the following outputs in accordance with the CFRAM brief:

- Maps of maximum flood depth for each AFA and MPW reach;
- Maps of maximum velocity for each AFA;
- Maps of maximum flood hazard for each AFA;
- Maps of maximum flood extent maps for each AFA and MPW reach;
- Maps of Flood Zones for each AFA and MPW reach;
- Specific Risk Number of Inhabitants maps;
- Specific Risk Types of Economic Activity maps; and,
- Specific Risk Density maps.

For AFAs, the gridded outputs from the 1D-2D models were used directly or processed to develop the flood maps as discussed below. or MPWs, the maximum water level from the 1D model nodes have been used to derive the flood depth and flood extents intersected with the DTM. It is important to note that no allowance has been made for the local urban drainage system for either AFAs or MPWs. Therefore, the flood maps assume flooding wherever modelled depth is greater than 0mm.

8.2 Flood Depth and Velocity Mapping

Maximum flood depth and velocity are output directly as GIS grids from the 2D models. The flood depth and velocity maps display the raw model results based on the 5m model grid without the need for any further processing. The flood depth and velocity maps are provided in the digital handover and print-ready maps.

1D water level lines (WLLs) were used to extract depth and velocity information from the 1D river channels in order to produce a seamless flood map. The WLLs plot the maximum water level symmetrically against the flow widths from the centreline in ISIS or ESTRY, which may not be appropriate for asymmetrical cross-sections at meander bends. Therefore, the in-channel water depths presented on the flood maps should be considered in conjunction with the detailed channel survey data presented in the 1D models.

For MPW reaches using a 1D only approach, water levels were assigned to the 1D cross –sections and interpolated to create a water level surface TIN which was then intersected with the DTM to derive flood depths. Any isolated or disconnected areas of flooding were manually reviewed to check whether the water level had overtopped the raised feature, such as a road embankment. The isolated flooding was removed if the maximum water level was below the raised feature crest. Conversely, the previously isolated flooding was connected if the maximum water level was above the raised feature crest. The greater spacing between MPW cross-sections may limit the confidence in flood depths in-between sections for the Womanagh upstream of Finisk Bridge. Downstream of Finisk Bridge the accuracy of the flood depths is limited by the accuracy of the IFSAR DTM. However the volume spilling over the raised embankments should be reasonable because the crest levels have been topographically surveyed for this study.

The same 1D mapping approach was taken to generate flood depth and extents in Ballingeary and Inchigeelagh based on the LIDAR DTM for these AFAs. Velocity grids were generated using the same TIN method to interpolated velocities values from each cross-section across the floodplain. This velocity surface was then clipped to the flood extent generated from the above approach.

8.3 Flood Hazard Mapping

The flood hazard was also output directly from the 2D model results, whereby flood hazard is a function of depth and velocity which is calculated for every time step to derive the maximum flood hazard based on the following equation that has been modified from the DEFRA FD2320 guidance to remove debris factor:

$$Flood\ Hazard = Depth\ x\ (Velocity + 0.5)$$

When interpreting flood hazard maps, it is important to consider that the flood hazard rating value has been calculated at each time-step based on concurrent depth and velocity. The maximum flood hazard rating value is the maximum of these concurrent flood hazard values but does not necessarily coincide with both the maximum depth and maximum velocity. This is produced directly by the TUFLOW model and requires no post-processing to derive flood hazard for 1D-2D models.

For the 1D-only model covering Ballingeary and Inchigeelagh AFAs, peak flood velocity was found to be coincident with peak flood depth within the AFA boundaries (Figures 8.1 and 8.2). Therefore the maximum flood depth grid was multiplied by the maximum flood velocity grid + 0.5, as set out in the equation above, to derive flood hazard for these AFAs.

Figure 8.1: Velocity and Depth Hydrographs in Ballingeary

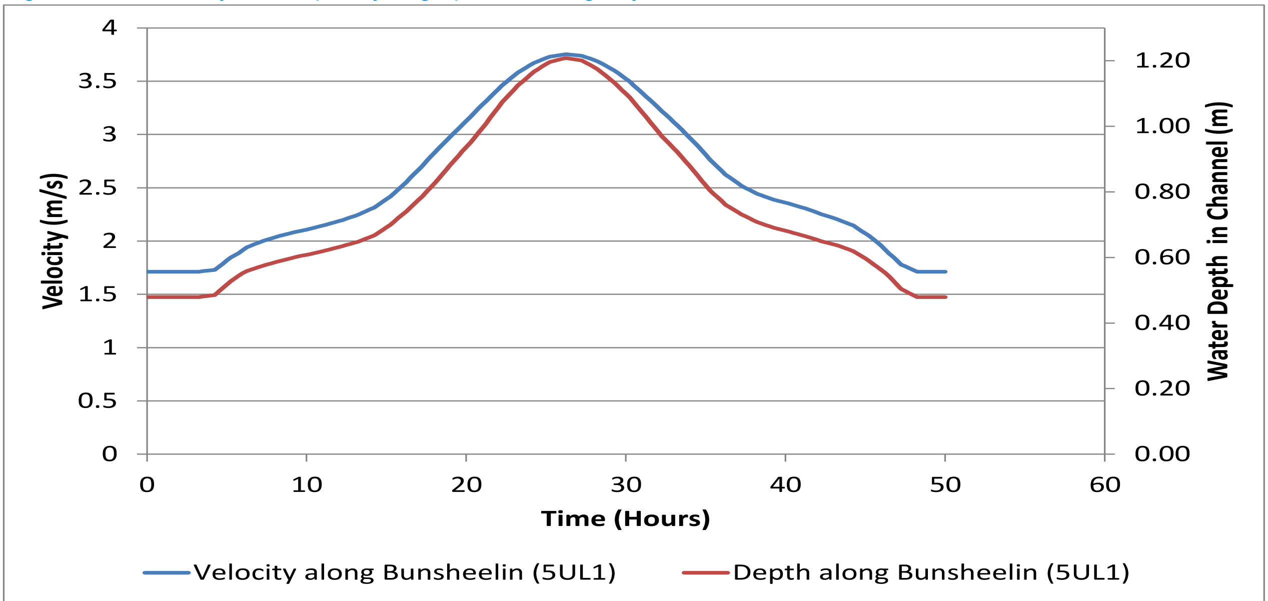
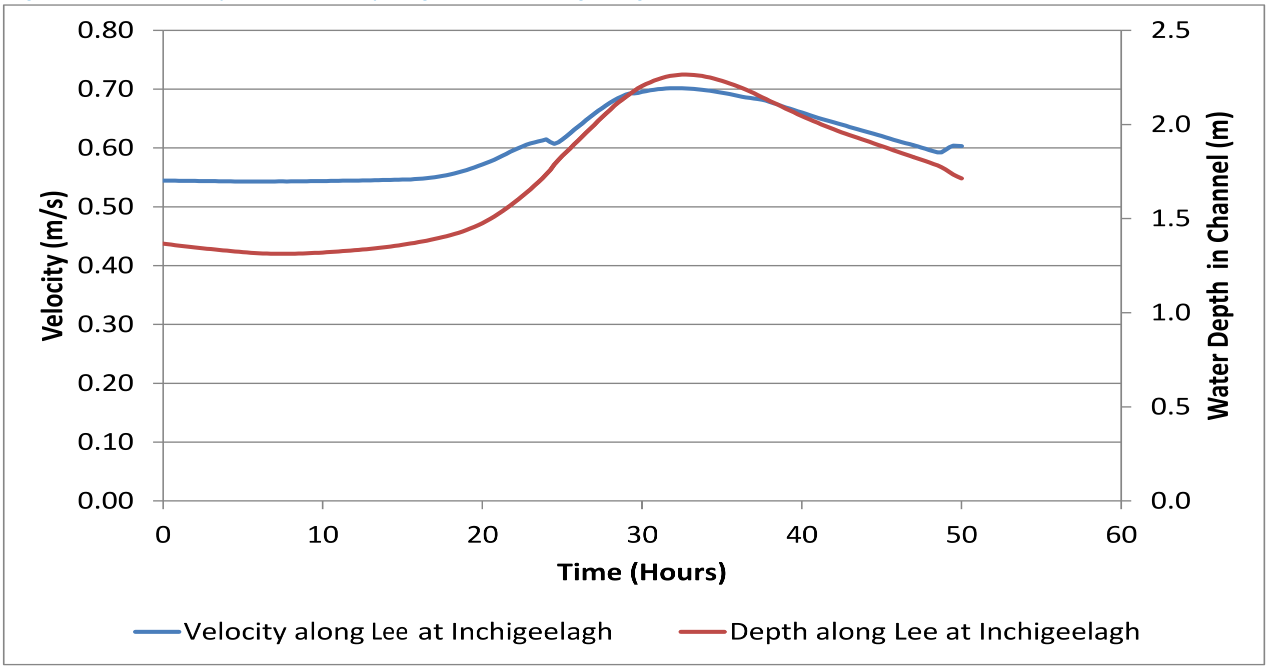


Figure 8.2: Velocity and Depth Hydrographs in Inchigeelagh



In accordance with CFRAM guidance, debris factor has not been considered given the uncertainties associated with variable debris factors based on the underlying land use.

The flood maps categorise the resultant flood hazard values into four broad classes (Table 8.1) which are presented on the flood hazard maps.

Table 8.1: Flood Hazard Categories

Flood Hazard Value	Degree of Flood Hazard	Description
<0.75	Low	Caution - “Flood zone with shallow flowing water or deep standing water”
0.75-1.25	Moderate	Dangerous for some (vulnerable social groups such as children and the elderly) - “Danger: Flood zone with deep or fast flowing water”
1.25-2.00	Significant	Dangerous for most people - “Danger: flood zone with deep fast flowing water”
>2.00	Extreme	Dangerous for all - “Extreme danger: flood zone with deep fast flowing water”

Source: DEFRA FD2320 Table 2 Hazard to People

8.4 Flood Extent and Zone Mapping

The maximum flood extent was derived from the maximum flood depth grid and converted to a closed polygon. The 2D model simulates all active flow paths so wet cells are connected at the maximum flood extent. The GIS processing automatically simplifies the polygon to give a smoother outline, but this does not differ from the modelled grid extent. No additional processing was undertaken to remove dry islands so that the flood outlines matched the modelled grids.

Flood Zone maps were produced for all models. Flood Zone A was derived from the 1%AEP fluvial and 0.5%AEP coastal extents. Flood Zone B was derived from the 0.1%AEP fluvial and 0.1%AEP coastal extents without formal flood defence schemes in place.

The raised embankments along the River Womanagh downstream of Finisk Bridge protect the coastal floodplain. The Flood Zone outlines and defended areas were derived from the 0.5% and 0.1%AEP extreme tide levels horizontally projected across the floodplain without the flood embankment in place. The standard of protection in the CFRAM Studies is considered to be the %AEP closest to the defence level but which does not cause flooding. The standard of protection varied from 50%AEP up to the 0.5% and 0.1%AEP across UoM19. The Defended Areas were then derived from the water levels for the relevant %AEP event without the flood embankment in place.

No other formal or informal effective flood defences were identified in the other AFAs considered. Therefore, the flood zone outlines are the same as the flood extents for the other AFAs.

8.5 Combined Flood Source Mapping

The Womanagh is subject to flooding from both fluvial and tidal influence. Therefore, the fluvial-dominant flood extent was merged with the tidal-dominant flood extent to produce the maximum flood extent from both sources. It should be noted that this does not represent a target %AEP assessed in the joint-probability, but provides a useful summary of the maximum extent from both sources.

8.6 Flood Risk (Assessment) Mapping

8.6.1 General Flood Risk Maps

The potential adverse consequences (risk) associated with flooding in each of the AFA's was assessed and mapped against four risk receptor groups:
- Society (including risk to people)
- The Environment
- Cultural Heritage
- The Economy

Maps were produced by overlaying flood extents for key AEP events on GIS datasets for each of the four receptor groups listed above. Separate maps were prepared for each receptor group.

8.6.2 Specific Flood Risk Maps

Specific Flood Risk maps are required for key indicators. These include the following:

- Indicative Number of Inhabitants
- Types of Economic Activity
- Economic Risk Density

8.6.2.1 Indicative Number of Inhabitants

For each AFA, the study area was broken into a number of grids, each 10,000m^2 (i.e. 1 ha). The population density per ha was calculated by summing the number of residential properties within each grid and multiplying by an average occupancy rate determined by the Central Statistics Office.

8.6.2.2 Types of Economic Activity

Within each AFA, the types of economic activity (i.e. property, infrastructure, rural and economic) at flood risk were identified. These were mapped on a UoM scale, where the types of economic activity at risk for each AFA was represented using the coded composite symbols in accordance with GN 26 (Table 8.2).

Table 8.2: Derived Datasets of Economic Activity at Risk

Economic Activity	Derived Dataset	Description
Buildings	Buildings in flood (DG)	Buildings located in modelled flood extents
Infrastructure	Infrastructure in flood extents(DI)	Existence of infrastructure in flood extent
Commercial	Commercial use within flood extents(DK)	Existence of commercial land use in flood extent
Rural	Rural land use in flood extents(DJ)	Existence of rural land use in flood extent

8.6.2.3 Economic Risk Density

The maximum depth of flooding was extracted for each building polygon for the full range of AEP events using the results of the hydraulic modelling and flood mapping. The calculation of flood damages was based on the Flood Hazard Research Centre Handbook of 2010 (FHRC, 2010) and the "Multi-Coloured Manual" of 2005 (FHRC, 2005) as referred to in FHRC 2010, subject to caveats, amendments and clarifications as set out in the National CFRAM Programme Guidance Note No.27 Rev C.

Damage costs were converted to euro by applying a Purchasing Price Parity multiplication factor and an inflation factor. For Residential Properties damage costs were calculated based on the depth of flooding and the corresponding unit cost of damage for property type. For Non-residential Properties damage costs were calculated based on the depth of flooding and the unit cost of damage for property type per m^2.

Following the calculation of the estimated cost of damages for the full range of AEP events, the Annual Average Damage (AAD) for each property will be calculated. The AAD for each property within each 100m^2 (i.e. 1 Ha) grid was summed and represented on a map providing the economic risk density (€ AAD / Ha).

9 Model and Mapping Results

9.1 Overview

The greatest fluvial flood risk in UoM19 is located in Ballingeary and Inchigeelagh based on the model predicted results and flood maps. Approximately 40 buildings are at risk in Ballingeary and 30 buildings are at risk in Inchigeelagh in the 1%AEP fluvial event. Regular flooding of properties was also predicted in the 5%AEP to 10%AEP in these AFAs. The model results also predicted approximately 5 buildings in Castlemartyr to be affected by flooding in the 20%AEP fluvial event, increasing to 20 buildings in the 1%AEP fluvial event.

Elsewhere, flood risk to properties and people was less. Flooding in Killeagh did not affect properties in the 1%AEP fluvial current event. Both fluvial flooding and coastal flooding affected less than 5 properties along the River Womanagh.

The following sections summarise the key findings for each AFA to highlight the flooding issues identified in the flood maps. A more detailed assessment of receptors at risk and implications for these receptors is discussed in the subsequent Flood Risk Assessment.

9.2 Ballingeary AFA

Map 9.1 summarises the fluvial flood risk in Ballingeary for the 10%, 1% and 0.1%AEP design scenarios. The key flow routes and flooding mechanisms predicted by the model are as follows:

- Lough Allua fills after prolonged rainfall as only a limited discharge can exit at Inchigeelagh Bridge downstream.
- This causes the water levels to rise and backup towards Ballingeary. This leads to flooding in Ballingeary when this backwater combines with excess flows on the Lee and Bunsheelin to flood properties.
- There are also reports of pluvial flooding from overland sheet flow down the valley sides and from the urban drainage system. However pluvial flooding is not within the scope of CFRAM studies.

The key thresholds and areas affected by flooding in Ballingeary are:

- 50%AEP event floods the school sports pitch, Casadh Na Spride Park, and floods up to the back of properties by the Post Office. This is caused by backwater in Lough Allua due to prolonged rainfall and limited capacity at Inchigeelagh Bridge.
- 20% AEP event floods Main Street and properties by the post office to Saint Finbarr's and Saint Ronan's Church. This is caused by a combination of high flows along the Bunsheelin River and backwater in Lough Allua due to prolonged rainfall/successive events.
- 20%-10%AEP floods over the R584 upstream of Ballingeary Bridge from the Upper Lee in accordance with the recurring flood reports and flood events in 2004 and 2005.

The greatest risk to life is associated with deep flooding at the back of Post Office and high velocities by Ballingeary Bridge. The rapid response of the Bunsheelin catchment when ground conditions are saturated could mean a rapid rise in water levels with little warning.

The key flood mechanisms in Ballingeary are a combination of backwater from Lough Allua after prolonged rainfall and overland flow over saturated ground.

However, the following features/structures also influence the severity of flood risk in Ballingeary:

- level/ channel capacity of the Bunsheelin and Lee Rivers downstream of the R584 to Lough Allua
- Inchigeelagh Bridge downstream of Lough Allua which limits the outflow and therefore the backwater along Lough Allua to Ballingeary.

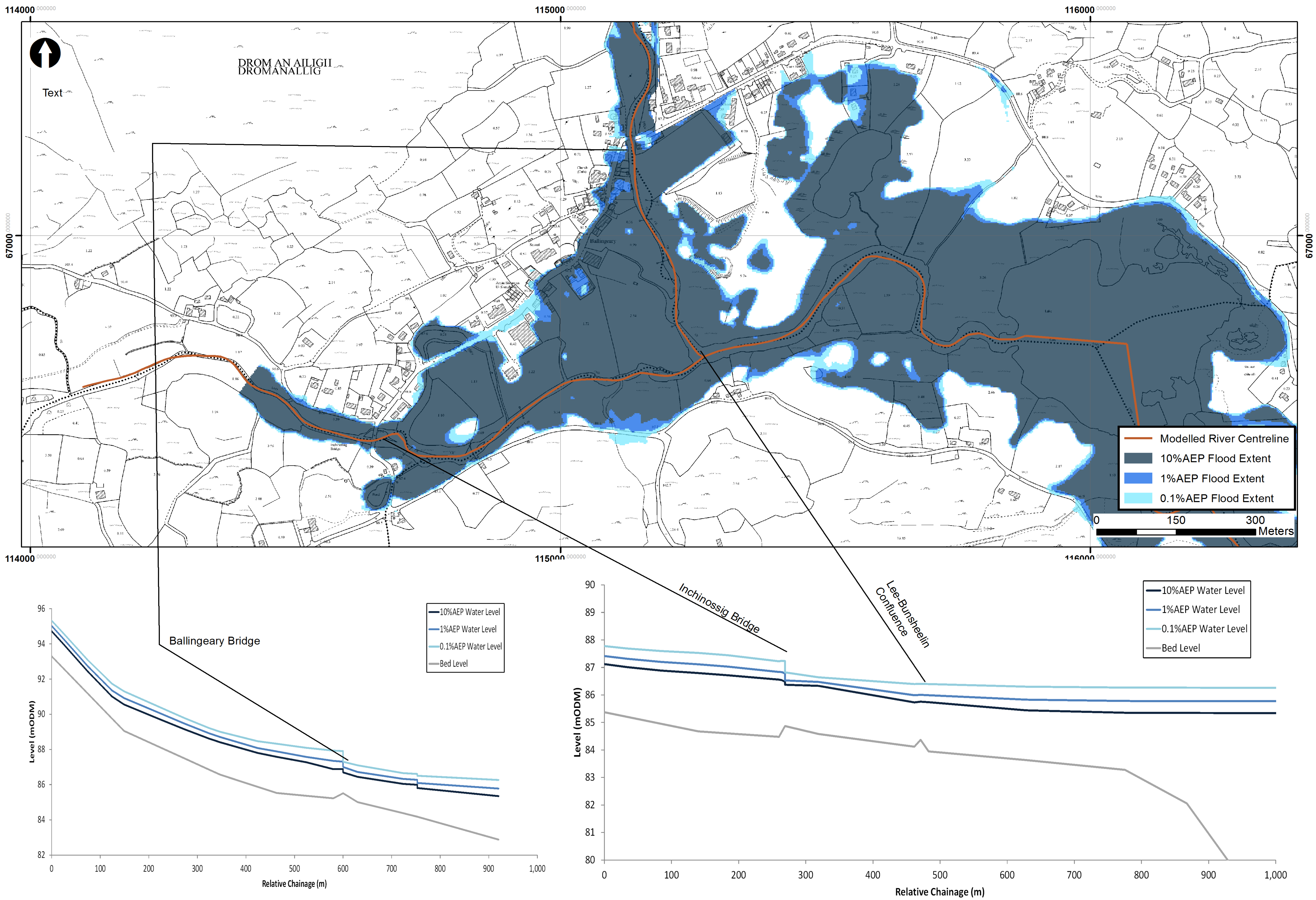
The areas flooded are consistent with the recurring flood reports and the flooding experienced in November 2009. The model has been calibrated to the flood levels and flood extent recorded in November 2009. Therefore there is reasonable confidence in the flood mapping in Ballingeary based on the information available at the time of this study.

The Ballingeary model has been shown to be sensitive to flow estimates and the duration of the flood hydrograph (or succession of flood events) which determine the volume available to fill Lough Allua. The design flood hydrograph takes a conservative assumption of 43 hour storm duration to represent similar mechanisms and volumes to the recorded flood events. Going forward, it would be beneficial to install a longer-term level gauge in Lough Allua to further assess the relationship between rainfall events and Lough level.

The following recommendations for flood risk management option development can be made:

- Increased conveyance of the Bunsheelin and Lee Rivers could reduce flood levels for small magnitude, more frequent events. Such measures are unlikely to increase flows (and flood risk) downstream as the additional flow would be small compared to the capacity of Lough Allua.
- Flood warning would be ineffective for flooding caused by overland flow in the upper reaches of the Bunsheelin as this source of flood risk is driven by small flashy catchments.
- However, flood warning would be more effective for flooding arising from backwater in Lough Allua where forecast rainfall is linked to the antecedent level in the Lough.

Map 9.1: Summary of Fluvial Flood Risk – Ballingeary



9.3 Inchigeelagh AFA

Map 9.2 summarises the fluvial flood risk in Inchigeelagh for the 10%, 1% and 0.1%AEP design scenarios. The key flow routes and flooding mechanisms predicted by the model are as follows:

- Lough Allua fills after prolonged rainfall as only a limited discharge can exit at Inchigeelagh Bridge downstream.
- This causes the water level to rise upstream of the bridge and eventually overtop the road to flood properties in Inchigeelagh.

The key thresholds and areas affected by flooding in Inchigeelagh are:

- 10%AEP event floods low lying areas at the back of Rose Cottage and flooding of the road by Inchigeelagh Bridge.
- 2% to 5%AEP event begins to cause flooding to properties at Rose Cottage on the right bank and Cuan Mhuire along the L3404 on the left bank as the bridge is bypassed.

The greatest risk to life is associated with deep flooding and high velocities upstream of Inchigeelagh Bridge and between the islands downstream of the bridge.

The critical structures that determine flood risk in Inchigeelagh are:

- Inchigeelagh Bridge.

The areas flooded are consistent with the recurring flood reports along the road and the flooding experienced in November 2009. The model has been calibrated to the flood levels and flood extent recorded in November 2009. Therefore there is reasonable confidence in the flood mapping in Inchigeelagh based on the information available at the time of this study.

The Ballingeary model, which includes Inchigeelagh AFA, has been shown to be sensitive to flow estimates and the duration of the flood hydrograph (or succession of flood events) which determine the volume available to fill Lough Allua. The design flood hydrograph takes a conservative assumption of a 43 hour storm duration to represent similar mechanisms and volumes as the recorded flood events. Going forward, it would be beneficial to install a longer-term level gauge in Lough Allua to further assess the relationship between rainfall events and Lough level.

The following recommendations for flood risk management option development can be made:

- Increased conveyance at Inchigeelagh Bridge could reduce levels upstream and flooding over the road and to properties. However, such measure could also increase flows (and flood risk) downstream.
- Flood warning could be effective for flooding arising from the level of Lough Allua.

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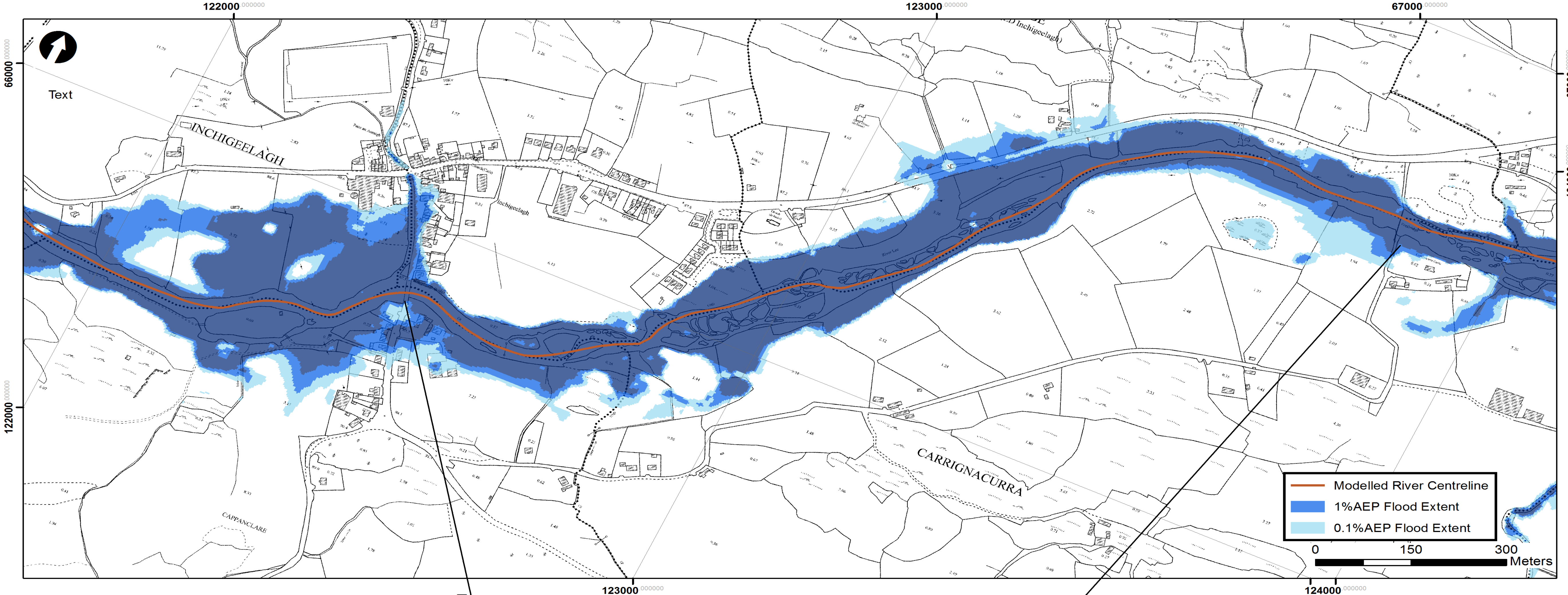
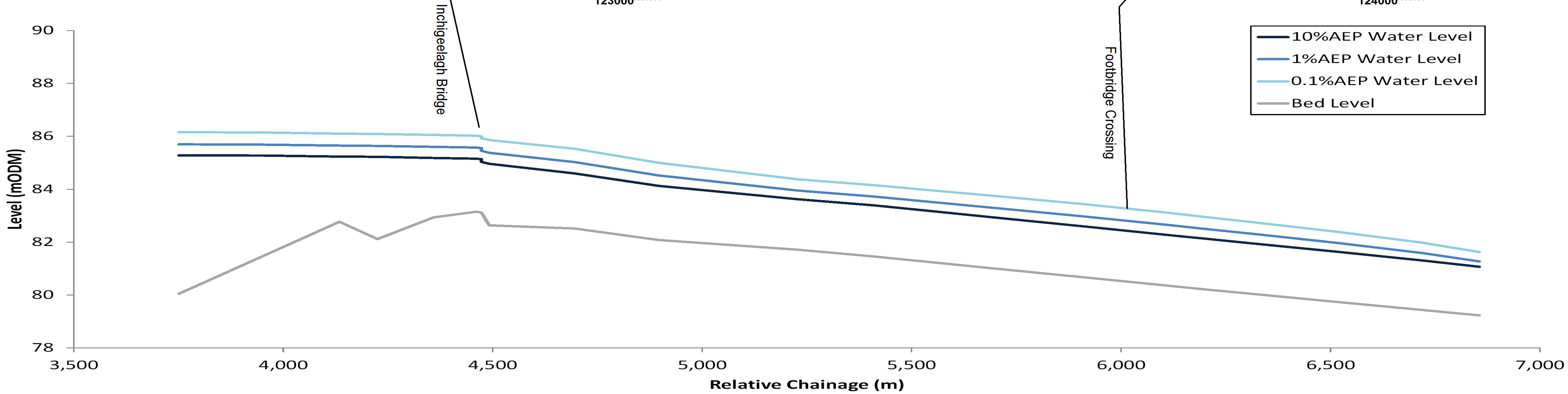
Map 9.2: Summary of Fluvial Flood Risk – Inchigeelagh





9.4 Castlemartyr AFA

Map 9.3 summarises the fluvial flood risk in Castlemartyr for the 10%, 1% and 0.1%AEP design scenarios. The key flow routes and flooding mechanisms predicted by the model are as follows:

- The River Kiltha overtops the left bank upstream of the town to join with the Killamucky tributary and flow towards the sink hole near the Enterprise Centre.
- Backwater from Castlemartyr and the access bridge spills over the left bank to flood properties along Mogeely Road.

The key thresholds and areas affected by flooding in Castlemartyr are:

- 20%AEP event causes extensive flooding of fields towards the Enterprise Centre although properties are not affected.
- 20%AEP event floods properties upstream of Castlemartyr Bridge due to backwater from both the main bridge and access bridge upstream.
- 10%AEP event floods over the N25 at Castlemartyr Bridge assuming the sink hole is saturated.
- 0.5%AEP event floods properties opposite Ladysbrook House.

The greatest risk to life is associated with deep flooding upstream of Castlemartyr Bridge. Flooding over the N25 at Castlemartyr Bridge may present a hazard to road users.

The critical structures that determine flood risk in Castlemartyr are:

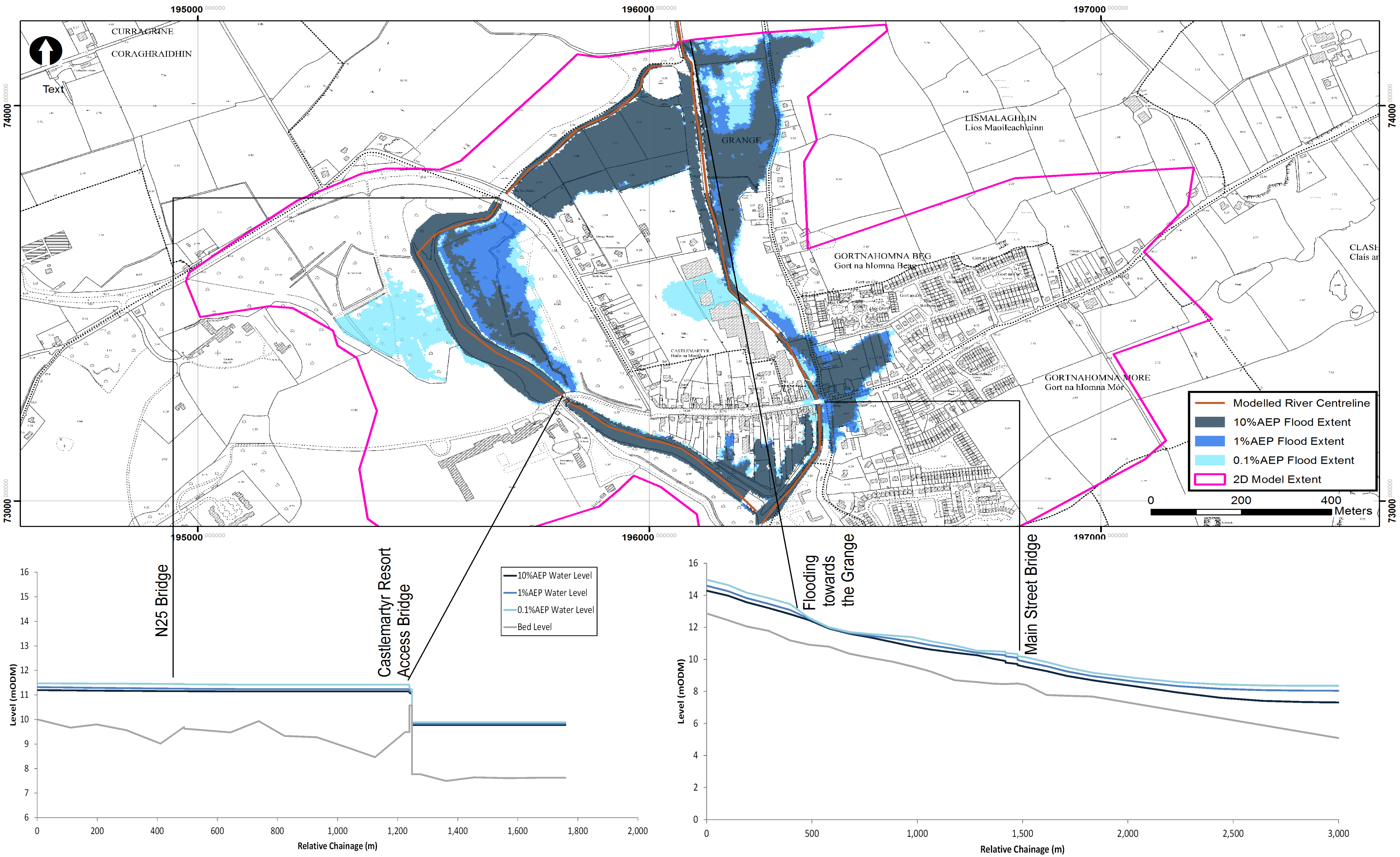
- Bank levels at the Killamucky confluence
- Castlemartyr Bridge
- Access Bridge

The areas flooded are consistent with the recurring flood reports from the local area engineer and the 2009 flood report. Modelled flooding is more extensive than reported to the east of Mogeely Road because it has been assumed that no water exits the catchment through the sink hole there as a conservative estimate of flood risk in Castlemartyr. The model has been calibrated to the flood levels and flood extent recorded in November 2009. Therefore there is reasonable confidence in the flood mapping in Castlemartyr based on the information available at the time of this study.

The following recommendations for flood risk management option development can be made:

- Increased conveyance and raised bank levels at the key structures identified are likely to reduce flood risk.
- Flood warning on the River Kiltha is likely to be effective as the time to peak is over 6 hours.
- The soil moisture deficit conditions (i.e. saturation) should be considered in the sizing and operation of any potential flood risk mitigation measures in this karstic catchment.

Map 9.3: Summary of Fluvial Flood Risk- Castlemartyr



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9.5 Killeagh AFA

Map 9.4 summarises the fluvial flood risk in Killeagh for the 10%, 1% and 0.1%AEP design scenarios. The key flow routes and flooding mechanisms predicted by the model are as follows:

- Overtopping of the Dissour upstream of the town and downstream at the Old Rail Bridge to flood fields. However properties are not affected by the flood waters.
- Backwater from the road bridge to flood the Old Thatch Pub in extreme fluvial events.

The key thresholds and areas affected by flooding in Castlemartyr are:

- 20%AEP event exceeds the capacity of the channel upstream of the town and 100m upstream of the Old Rail Bridge to flood fields, but does not affect properties.
- 0.5%AEP event spills out-of-bank upstream of the Main Street Bridge to inundate the Old Thatch Pub, but does not reach the soffit level or overtop the road.
- This is consistent with local residents' experiences who have not witnessed flooding at the pub in living memory.

The greatest risk to life is associated with flooding at the Old Thatch Pub Area in extreme fluvial events. The flood hazard is classed as low to moderate due to the moderate depths of flooding and relatively low velocity of water.

The critical structures that determine flood risk in Killeagh are:

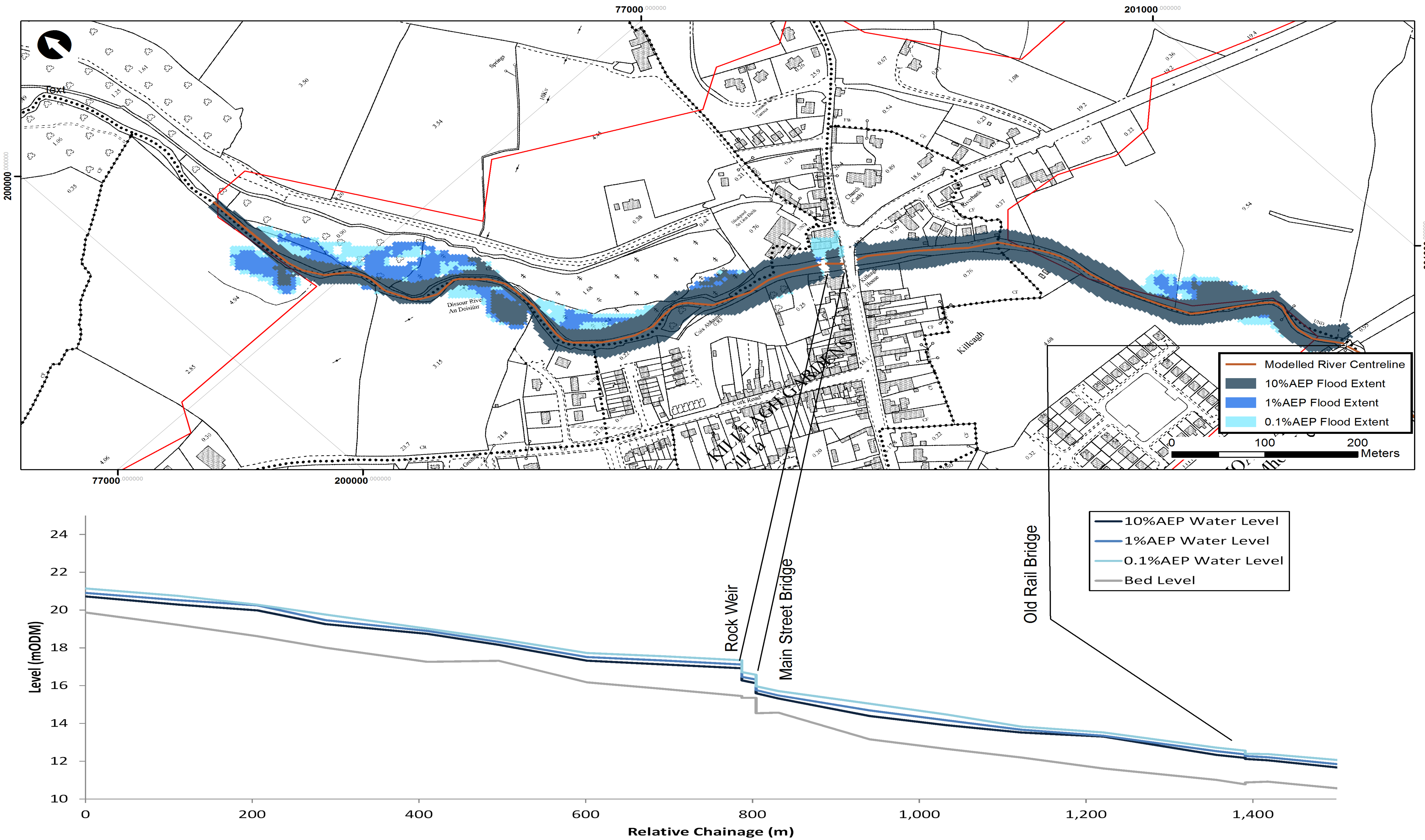
- Main Street Bridge and weir immediately upstream.

The areas flooded are consistent with the interview undertaken during the flood risk review, with no flooding experienced at the pub within living memory. The one flood report for Killeagh is actually located outside the AFA in the Balling catchment. Sensitivity tests have shown the model is not sensitive to hydrologic and hydraulic parameters. Therefore there is reasonable confidence in the flood mapping in Killeagh based on the information available at the time of this study.

Flood risk to properties in Killeagh is generally low. However, the following recommendations for flood risk management option development can be made:

- Increased conveyance and/or bank levels at the Main Street Bridge identified are likely to reduce flood risk.
- Flood warning on the Dissour is likely to be effective as the time to peak is over 6 hours.

Map 9.4: Summary of Fluvial Flood Risk – Killeagh



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10 Summary and Recommendations

10.1 Key Findings

The hydraulic analysis for UoM19 has developed four hydraulic models to assess current and future flood risk from the 50%, 20%, 10%, 5%, 2%, 1%, 0.5% and 0.1%AEP fluvial and tidal flood events. The design flood levels and flows were then processed to map flood extent, flood depth, flood velocity and flood hazard in the fours AFAs and one MPW.

Historic flood events

- The Ballingeary and Castlemartyr models were calibrated to the November 2009 flood event and recurring flood events.
- In Ballingeary, the hydraulic model matched well with the reported flood levels and extents except at Casadh Na Spride Park and upslope of the Church where overland flow added to the reported flooding. However, pluvial flooding is not within the scope of CFRAM studies.
- In Inchigeelagh, the hydraulic model matched well with reported levels and represented the backing up of water upstream of the Bridge to overtop the road and affected properties as reported in November 2009 and other similar events.
- In Castlemartyr, the model matched well with the reported flood levels and overtopping of the left bank at Mogeely Road. However it overestimated flood extent behind Mogeely Road because the sink hole was assumed in the modelling to be saturated as a worst-case scenario.
- The Killeagh and Womanagh models could not be fully calibrated as there were no flood levels or extents to calibrate to.
- Along the Womanagh, reported coastal flooding in 2004 was equivalent to the 0.1%AEP or greater magnitude events based on the ICPSS levels which correspond to flooding on the left and right banks upstream of Crompaun Bridge in the 0.1% coastal current event. However, the relative flood frequency estimate is suspect and could be improved by a review of Ballycotton tidal gauge data as the longer record becomes available.

Sensitivity test results

- Flood risk in Ballingeary and Inchigeelagh is sensitive to both uncertainties in peak flow and particularly sensitive to the uncertainties of the storm duration. These parameters determine the flood volume to fill Lough Allua and cause flooding in both these AFAs.
- Flood risk along the lower Womanagh is sensitive to uncertainties in the total tide plus surge level because large areas of low-lying land quickly become inundated once the River Womanagh overtops the raised tidal embankments.
- Flood risk to property in all the fluvial-dominated models was found not to be sensitive to the downstream boundary assumptions
- None of the UoM19 models were found to be sensitive to Manning's 'n' at the 1%AEP because the 1%AEP event already floods the majority of the floodplains and the small increase in levels did not cause a significant increase in flooding to properties.

Model and mapping results

The hydraulic modelling and mapping results were analysed for the design scenario under current conditions, the mid-range future scenario and high end future scenario. The key findings are summarised below.

- Of the AFAs assessed in UoM19, the greatest fluvial flood risk is located in Ballingeary and Inchigeelagh.
- Approximately 40 buildings are at risk in Ballingeary and 30 buildings are at risk in Inchigeelagh in the 1%AEP fluvial event. Regular flooding of properties was also predicted in the 5%AEP to 10%AEP in these AFAs.
- The model results also predicted approximately 5 buildings in Castlemartyr to be affected by flooding in the 20%AEP fluvial event, increasing to 20 buildings in the 1%AEP fluvial event.
- Elsewhere, flood risk to properties and people was less. Flooding in Killeagh did not affect properties in 1%AEP fluvial current event. Both fluvial flooding and coastal flooding affected less than 5 properties along the River Womanagh.

10.2 Recommendations

The following recommendations can be drawn from the key findings above for the subsequent flood risk assessment, preliminary option development and FRMP:

- The uncertainty and sensitivity to peak flow and duration estimates should be considered in the sizing and operation of any flood management measures in Ballingeary and Inchigeelagh.
- The uncertainty in the total tide plus surge levels should also be considered in the development of any flood embankment/walls to protect against coastal flooding along the Womanagh.
- Increased maintenance of channels as an independent measure is unlikely to manage flood risk at the 1%AEP for any of the AFAs assessed. It may be more effective for more frequent events and/or in combination with other measures.
- The capacity of Inchigeelagh Bridge, Ballingeary Bridge and Castlemartyr Bridge should be carefully considered for increased conveyance options to reduce flood risk upstream, as these have been shown to be critical during the calibration and sensitivity tests.

The following recommendations can be drawn from the hydraulic analysis for future analysis in the UoM19:

- It is recommended that longer-term level data is obtained for Lough Allua to better assess the relationship between rainfall, the capacity of the Lough and flooding in Ballingeary and Inchigeelagh.
- It is recommended that post-flood surveys are continued for all significant future flood events where properties and/or infrastructure are affected. Data should be collected shortly after the event and include: sources of flooding, timing of overtopping, any actions taken and at what time, blockages of structures, flood levels in the channel and on the floodplain and accompanying photographs.
- It is recommended that surface water flooding and the interaction of flooding with the urban drainage network is investigated in Ballingeary, given the history of pluvial flooding along Ardan Seamus o'Shea.

Glossary

AAD	Annual Average Damage: Average damage per year that would occur in a nominated development situation from flooding over a very long period of time.
AEP	Annual Exceedance Probability; this represents the probability of an event being exceeded in any one year and is an alternative method of defining flood probability to 'return periods'. The 10%, 1% and 0.1% AEP events are equivalent to 10-year, 100-year and 1000-year return period events respectively.
AFA	Area for Further Assessment – Areas where, based on the Preliminary Flood Risk Assessment and the CFRAM STUDY Flood Risk Review, the risks associated with flooding are potentially significant, and where further, more detailed assessment is required to determine the degree of flood risk, and develop measures to manage and reduce the flood risk.
AMAX	Annual Maximum Flood
CFRAM	Catchment Flood Risk Assessment and Management – The 'CFRAM' Studies will develop more detailed flood mapping and measures to manage and reduce the flood risk for the AFAs.
DTM	Digital terrain model; elevation of the bare ground surface without any objects like plants, buildings and man-made structures.
EU	European Union
EPA	Environmental Protection Agency
FRMP	Flood Risk Management Plan. This is the final output of the CFRAM study. It will contain measures to mitigate flood risk in the AFAs.
FRR	Flood Risk Review – an appraisal of the output from the PFRA involving on site verification of the predictive flood extent mapping, the receptors and historic information.
FSU (WP)	Flood Studies Update (Work Package) (2008 to 2011)
FSR	Flood Studies Report (HR Wallingford, 1975)
GIS	Geographical Information Systems
HA	Hydrometric Area. Ireland is divided up into 40 Hydrometric Areas.
HEFS	High-End Future Scenario to assess climate and catchment changes over the next 100 years assuming high emission predictions from the International Panel on Climate Change.
HEP	Hydrological Estimation Point
HPW	High Priority Watercourse. A watercourse within an AFA.
ICPSS	Irish Coastal Protection Strategy Study (2012)
ICWWS	Irish Coastal Water Level and Wave Study (2013)
IFSAR	Inter-ferometric Synthetic Aperture Radar used to derive ground elevation remotely from satellite platforms.

ING	Irish National Grid system, Ordnance Survey of Ireland
LiDAR	Light and Detection Ranging used to derive ground elevations from ground based or aerial platforms.
MPW	Medium Priority Watercourse. A watercourse between AFAs, and between an AFA and the sea.
MRFS	Mid-Range Future Scenario to assess climate and catchment changes over the next 100 years assuming medium emission predictions from the International Panel on Climate Change.
ODM	Ordnance Datum Malin.
	The current geodetic datum of Irish National Grid which references the mean sea level at Malin Head between 1960 and 1969.
OPW	Office of Public Works, Ireland
OSI	Ordnance Survey Ireland
PFRA	Preliminary Flood Risk Assessment – A national screening exercise, based on available and readily-derivable information, to identify areas where there may be a significant risk associated with flooding.
QMED	Median annual flood used as the index flood in the Flood Studies Update. The QMED flood has an approximate 50%AEP.
SAAR	Standard average annual rainfall 1961 to 1990
SEA	Strategic Environmental Assessment. A high level assessment of the potential of the FRMPs to have an impact on the Environment within a UoM.
SW CFRAM	South Western Catchment Flood Risk Assessment and Management study
UoM	Unit of Management. The divisions into which the RBD is split in order to study flood risk. In this case a HA.
UPO-ERR Gamma Curve	Unit-Peak-at-Origin Gamma curve coupled with an Exponential Replacement Recession curve. Developed in the Flood Studies Update Work Package 3.1 Hydrograph Width Analysis to derive design flood hydrographs.
WFD	Water Framework Directive. A European Directive for the protection of water bodies that aims to, prevent further deterioration of our waters, to enhance the quality of our waters, to promote sustainable water use, and to reduce chemical pollution of our waters.