RPS

NORTH WESTERN
NEAGH BANN
CFRAM
STUDY
CATCHMENT FLOOD RISK
ASSESSMENT AND MANAGEMENT

North Western - Neagh Bann CFRAM Study

UoM 06 Hydraulics Report

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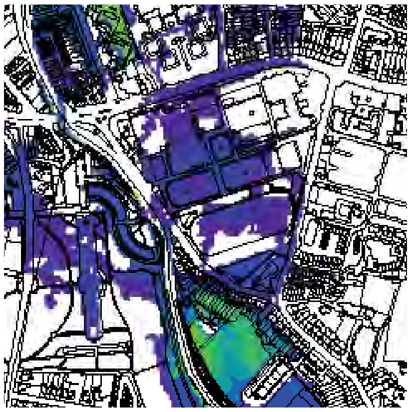

OPW
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Photographs of flooding on cover provided by Rivers Agency

North Western – Neagh Bann CFRAM Study

UoM 06 - Hydraulics Report

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ABBREVIATIONS

AEP	Annual Exceedance Probability
AFA	Area for Further Assessment
AMAX	Annual Maximum
CFRAM	Catchment Flood Risk Assessment and Management
CORINE	Coordination of Information on the Environment
DDF	Depth Duration Frequency
DHI	Danish Hydraulics Institute
DTM	Digital Terrain Model
ERBD	Eastern River Basin District
ESB	Electricity Supply Board
FARL	Flood Attenuation from Rivers and Lakes
FEM-FRAMS	Fingal East Meath Catchment Flood Risk Assessment and Management Study
FRA	Flood Risk Assessment
FRMP	Flood Risk Management Plan
FSU	Flood Studies Update
GDSDS	Greater Dublin Strategic Drainage Study
GPU	Graphical Processing Units
HA	Hydrometric Area
hDTM	hydrologically-corrected Digital Terrain Model
HEFS	High End Future Scenario (Climate Change)
HEP	Hydrological Estimation Point
HPW	High Priority Watercourse
ICM	Integrated Catchment Modelling
ICPSS	Irish Coastal Protection Strategy Study
IfSAR	Interferometric Synthetic Aperture Radar
INFOMAR	Integrated Mapping for the Sustainable Development of Ireland's Marine Resource
ISTM	Irish Surge and Tidal Model
LA	Local Authority
LiDAR	Light Detection and Ranging

MHWS	Mean High Water Springs
MPW	Medium Priority Watercourse
MRFS	Mid Range Future Scenario (Climate Change)
NWNB	North Western – Neagh Bann (River Basin District)
NDTM	National Digital Terrain Model
OD	Ordnance Datum
OPW	Office of Public Works
OSi	Ordnance Survey Ireland
PFRA	Preliminary Flood Risk Assessment
RBD	River Basin District
RMSE	Root Mean Square Error
SI	Statutory Instrument
UoM	Unit of Management

EXECUTIVE SUMMARY

To be completed in F03 version of report

1 INTRODUCTION

1.1 BACKGROUND TO STUDY AREA

The Office of Public Works (OPW) commissioned RPS to undertake the North Western – Neagh Bann Catchment Flood Risk Assessment and Management (CFRAM) Study in March 2012. The North Western – Neagh Bann CFRAM Study was the sixth and last CFRAM Study to be commissioned in Ireland under the EC Directive on the Assessment and Management of Flood Risks, 2007 as implemented in Ireland by SI 122 of 2010 European Communities (Assessment and Management of Flood Risks) Regulations, 2010.

The North Western International River Basin District (IRBD) covers an area of approximately 12,320 km^2 with approximately 7,400 km^2 of that area in the Republic of Ireland. Ireland's portion of the district includes two Units of Management (UoMs); UoM 01 (Donegal) and UoM 36 (Erne) which takes in all of County Donegal as well as parts of Leitrim, Cavan, Monaghan, Longford and Sligo. There is historical evidence of a high level of flood risk within certain areas of the district, with significant coastal and fluvial flooding events having occurred in the past.

The Neagh Bann IRBD covers an area of 8,120 km^2 with approximately 2,010 km^2 of that area in the Republic of Ireland. The Irish portion represents one single Unit of Management, UoM 06 (Neagh Bann) which takes in parts of counties Louth, Meath, Cavan and Monaghan.

This hydraulic report describes UoM 06 which includes hydrometric areas 03 and 06. It covers an area of 1,779 km^2 and includes the majority of County Louth, much of County Monaghan and parts of Meath and Cavan. The principal rivers in UoM 06 are the Fane, Glyde and Dee rivers (which flow eastwards into the Irish Sea) and the Blackwater River (which flows over the border into Northern Ireland in the northern reaches of the UoM).

UoM 06 is predominantly rural with the largest urban areas being Dundalk, Monaghan and Ardee. Smaller towns and villages include Castleblayney and Carrickmacross. Much of UoM 06 is given over to agriculture with some small areas of forestry and peatland cover.

Within UoM 06 there are nine Areas for Further Assessment (AFA) which were reported to the EU in March 2012. These are: Monaghan; Iniskeen; Carrickmacross; Ardee; Carlingford; Greenore; Dundalk & Blackrock South; Annagassan; and Termonfeckin.

The full list of AFAs within UoM 06 is shown in Table 1.1 and Figure 1.1, which also describes the associated flood source, fluvial and/or coastal, requiring assessment under this CFRAM Study.

Table 1.1: Fluvial and Coastal Flood Risk at each AFA

AFA/HPW	Fluvial Risk	Coastal Risk
Monaghan	✓	-
Iniskeen	✓	-
Carrickmacross	✓	-
Ardee	✓	-
Carlingford	✓	✓
Greenore	✓	✓
Dundalk and Blackrock South	✓	✓
Annagassan	✓	✓
Termonfeckin	✓	✓

Figure 1.1: UoM 06 AFA Locations and Extents

1.2 OBJECTIVE OF THIS HYDRAULICS REPORT

The objective of this hydraulics report is to set out the work and analysis undertaken in relation to, and the findings and conclusions of, the surveys and hydraulics analysis as defined within Section 7.8 of the Generic (Stage 1) Project Brief (Ref 2149/RP/002/F, May 2010), hereafter termed "the Stage 1 Project Brief". The report will detail any assumptions made, including the need for such assumptions and their justification, supporting discussion and appended information as necessary.

Under the North Western - Neagh Bann CFRAM study, UoM 06 includes nine AFAs, (refer to Table 1.1) which has required the development of nine models for flood risk analysis.

This report has been structured so that each AFA is reported on in a detailed and concise tabulated manner withunder Chapter 4. This approach enables the systematic and transparent reporting of every aspect of the hydraulic modelling process, detailing the work that has been undertaken with justification and assumptions clearly stated for each individual model. This avoids unnecessary repetition of generic information relating to all models or UoM 06 as a whole. Such information is provided within Chapters 1 to 3 to set the scene for the hydraulic analysis and provide ample background information.

The modelling referenced in detail for each of the AFAs under Chapter 4 includes the following topics:

- General Hydraulic Model Information
- Hydraulic Model Schematisation
- Hydraulic Model Construction
- Sensitivity Analysis
- Hydraulic Model Calibration and Verification
- Hydraulic Model Assumptions, Limitations and Handover Notes

This provides an easily accessible single source of reference for each AFA in terms of specific model inputs, approaches and outputs which can be readily utilised in future.

The report does not aim to provide a first principles explanation of hydraulic modelling theory, nor is it intended as a guidance document on how modelling software works.

2 DATA COLLECTION, SURVEYS AND DATA REVIEW

The process of data collection for the North Western - Neagh Bann CFRAM Study as a whole has been ongoing since Project Inception and is detailed in the North Western - Neagh Bann CFRAM Study, UoM 06 Inception Report (IBE0700Rp0002, 2013), hereafter termed "The Inception Report". Data specific to hydraulic analysis is described as follows.

2.1 HYDROLOGICAL DATA

2.1.1 Fluvial Hydrological Data

The availability of hydrometric data within UoM 06 is detailed in the North Western - Neagh Bann CFRAM Study, UoM 06 Hydrology Report (IBE0700Rp0006, 2014), hereafter termed "The Hydrology Report".

In general UoM 06 can be considered to be a moderately well gauged catchment with five of the nine distinct AFAs having flow data available from one or more hydrometric gauging stations located on the modelled watercourses. The six gauging stations in these five models each have either:

1. A FSU rating classification indicating confidence in the rating at Q_{med} or;
2. Been subject to rating review through hydraulic modelling such that confidence in the rating at Q_{med} is achieved (refer to Hydrology Report for full details on methodology and results of rating review analysis).

The existing hydrometric data has been utilised as much as possible to inform hydrological analysis and the subsequent derivation of:

The existing hydrometric data has been utilised as much as possible to inform hydrological analysis and the subsequent derivation of:

1. Historical flood event peak flows and hydrographs – those used for hydraulic model input / boundaries and calibration of each model are detailed in the Inception Report and Chapter 4 of this report, Section 4.1.5 to Section 4.9.5 respectively.
2. Design flows and hydrographs for the required present day Annual Exceedance Probabilities (AEPs) ranging from 50% to 0.1% and future scenarios –refer to Hydrology Report for full details of hydrological analysis and design flow estimation for both gauged and ungauged catchments.

The integration of hydrological and hydraulic analysis is at the core of the methodology undertaken in this Study in arriving at final hydraulic modelling outputs. This is discussed further in Section 3.6 and detailed per AFA/model under Chapter 4.

2.1.2 Tidal Data

The Hydrology Report (Section 6.2) discusses the use of tidal data within the Study. This data has been taken from the Irish Coastal Protection Strategy Study (ICPSS) and is discussed further in Section 3.8 of this report.

2.1.3 Rainfall Data

Trials undertaken within the Eastern CFRAM Study area demonstrated that there were benefits to be had by using gauge adjusted radar, as opposed to using rain gauge data only, to drive rainfall runoff models. A review of the extents of the radar coverage available found that there was some coverage of the North Western – Neagh Bann Study area from the Met Office radar at Castor Bay and the Met Éireann radar at Dublin Airport.

However, as the Study area is generally well gauged and there is already high temporal resolution rainfall data from the hourly gauges in close proximity to the potentially benefitting catchments, processing of the radar records into gauge adjusted, gridded and catchment aggregated time series was not considered necessary for UoM 06.

Full details of rainfall data analysis and associated hydrological modelling are provided in the Inception Report and Hydrology Report.

Rainfall data has also been used as direct input to integrated run-off / hydraulic models in UoM 06 in cases where the statistical based and catchment run-off based hydrology approach was deemed to be unrepresentative of catchment performance. In these cases the statistical catchment based design flows were superseded with the requirement for rainfall data time series profiles used as direct input to integrated models (refer to Hydrology Report, Chapter 4; and Section 3.2 - 3.5 and Chapter 4 of this report). Rainfall is applied as a time series input file and derived from the same sources as listed above (rainfall radar and hourly rain gauges) for calibration events. For design events, Depth Duration Frequency (DDF) Model outputs from the OPW Flood Studies Update (FSU) Work Package 1.2 have been extracted from the FSU DDF gridded data for mid catchment grid points to derive rainfall depths in millimetres for each design AEP. For each design event a range of rainfall sums representing different depth / duration combinations for the relevant AEP (frequency) were applied to the rainfall run-off component of the integrated catchment hydrological / hydraulic model to ascertain the critical storm duration for flood mapping. These sums were distributed to summer and winter Flood Studies Report (FSR) storm profiles as appropriate. Full details of this approach are included in the Hydrology Report, Chapter 4. The AFAs/HPWs to which integrated catchment modelling has been applied are outlined in Section 3.2 of this report and detailed under Chapter 4.

2.2 TOPOGRAPHICAL SURVEY DATA

2.2.1 Digital Elevation/Terrain Models

As detailed in the Inception Report, the OPW provided National Digital Height Model (NDHM) (5m resolution IfSAR) data covering UoM 06 in its entirety at the project outset.

In addition to this data, the OPW also provided hydrologically-corrected Digital Terrain Model data (hDTM). These data were presented in a 20m resolution, covered the entire spatial extent of UoM 06 and were hydrologically corrected.

On receipt of this information, RPS reviewed the datasets in order to check for adequate project areal coverage. As the xyz data had already been converted into ESRI Grid files, no further post-processing was required for geographical data visualisation.

2.2.2 Floodplain Survey

The Stage 1 Project Brief indicated that the OPW would supply the results of a floodplain survey by May 2012; however delivery of some of the processed floodplain survey information was delayed until September 2012 due to weather issues during the fieldwork period. This survey utilised airborne laser scanning technology (LiDAR - Light Detection and Ranging). The Inception Report has already discussed how RPS provided input into the required coverage of this survey. On receipt of the LiDAR information, RPS reviewed and validated the extent of its spatial coverage. This was efficiently performed via the superimposition of multiple ESRI ArcGIS shape-files of the data. This methodology allowed for rapid visualisation and subsequent identification of any geographical inadequacies. If supplied LiDAR information was found to contain insufficient coverage of AFAs and HPWs (areas designated for two-dimensional modelling); then these areas were targeted for rectification and additional LiDAR requested or alternative datasets were utilised. Figure 2.1 illustrates the extent of LiDAR coverage in UoM 06 in relation to modelled watercourses.

The DTM derived from the received LiDAR data was assumed to meet the vertical accuracy as specified in the Stage 1 Project Brief - 0.2m RMSE. Given the quality of the received surveys, additional manipulation or post-processing work was not required for the LiDAR data at HA level.

Where localised post-processing work has been undertaken at an AFA/Model level, the details have been provided under Chapter 4.

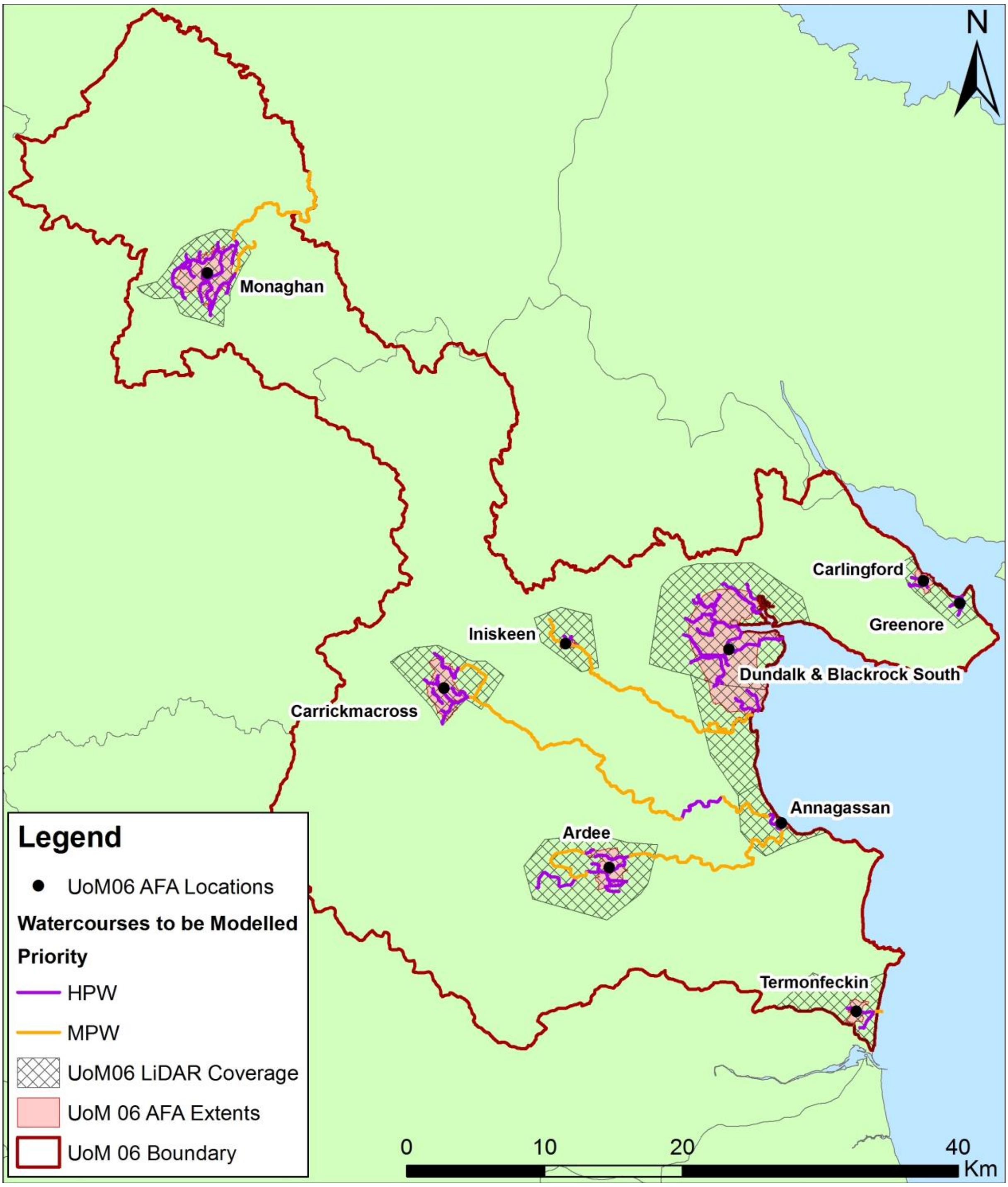

Figure 2.1: Extent of LiDAR Coverage in UoM 06

2.2.3 Coastal Bathymetry

Bathymetric data was required for all models located within areas of tidal influence. Those areas with no direct coastal inundation required basic bathymetric data in the vicinity of the mouth of the relevant rivers. Those areas subject to complex coastal inundation required more detailed and extensive bathymetric data. In those cases, sufficient offshore data was required to represent the various

channels, drying zones and offshore banks within the model domain. Details of coastal bathymetry data used per model are included under Chapter 4.

Some parts of the bathymetry information used in the models was obtained from INFOMAR survey data, a joint venture between the Geological Survey of Ireland (GSI) and the Marine Institute, supplemented with Admiralty Chart data, as digitally supplied by C-Map of Norway.

The OPW LiDAR data provided as part of this study, in conjunction with the OPW LiDAR commissioned as part of the Irish Coastal Protection Strategy Study (ICPSS), along with significant numbers of more localised hydrographic surveys already in existence, were used to provide specific information for inshore and overland areas. Where necessary, the OPW LiDAR data was trimmed to the Ordnance Survey Ireland (OSI) High Water Mark, in order to remove areas containing water level elevations, rather than bare earth data and combined with other datasets to provide complete coverage of the model domain where necessary.

In areas where no other data was available, the National Digital Height Model (NDHM) was included in the models, although it was noted that it is of lesser accuracy to the OPW LiDAR data.

RPS processed and quality checked all bathymetric data to ensure its suitability for use within the modelling systems, consistently ensuring that any model interpolation processes produced valid meshes which were representative of the input data. Where relevant, buffers were used between adjoining datasets, in order to ensure a smooth transition. The data, having been checked, was deemed appropriate for use in the models.

2.2.4 Channel and Structure Survey Data

The most significant aspect of data collection since the inception stage of the North Western - Neagh Bann CFRAM Study has been the capture of channel and structure survey data to provide cross-section and long-section information (x, y, z spatial coordinates) of river channels and banks, on-line channel structures (bridges, weirs, sluices, etc.) and flood defences (walls, embankments, etc.). This information is necessary for the development of hydraulic models of the High Priority and Medium Priority Watercourses (HPW and MPWs) within UoM 06.

JBA Consulting commenced the preparation of documentation to procure a channel and cross-section survey contract for most of the area within UoM 01 on behalf of the OPW as part of a pre-contract national survey management programme. RPS were subsequently tasked with completing the survey specification, procuring a survey contractor to complete UoM 01 and also preparing contract documents for the required channel and cross-section surveys within UoM 06 and UoM 36. Due to the emerging timescales and proximity of the works, these contracts were merged in mid 2012 under one contract to provide the full survey requirements on the three Units of Management within the North Western and Neagh Bann CFRAM Study area. This survey contract (known nationally as SC7) encompassed the full channel cross-sections, details of hydraulic structures and a geometric survey of defences for UoM 01, 06 and 36.

The specific tasks undertaken, all of which will relate to the building of hydraulic models were:

- Establishment of suitable survey control along the survey areas;
- Survey of river channel cross sections, at prescribed locations within the survey areas;
- Survey of relevant structures identified within the survey areas;
- Survey of identified flood defences within the survey areas;
- Delivery of outputs as appropriate to the nature of the survey;

The raw survey data was provided electronically in the following formats:

- ISIS input format (also compatible with ICM);
- MIKE input format;
- Cross-section XYZ format;
- Left & Right Bank Only XYZ format: This includes integrated cross-section crest levels, flood defence crest levels and any intermediate bank levels surveyed between cross sections, provided in a separate XYZ file for each bank;
- GIS shapefiles of surveyed watercourse centrelines and channel cross sections with populated attribute tables showing Reach IDs, chainages, and coordinate data;
- AutoCAD drawings;
- Georeferenced site photographs and videos;
- Digital metadata.

Specific details of the survey data received can be found under Chapter 4. The survey contract for SC7 comprised eight pre-defined work packages, of which four work packages related to UoM 06. The surveys were carried out by Murphy Surveys Ltd between 25th January 2013 and 17th July 2013. Incoming survey data was received and quality checked using the following process:

- Cross references of data i.e. cross section crest levels against long section levels at the same point.
- Reviewing cross-section locations to assess significant changes in channel width and coverage of structures (this step was largely completed at the site visit / specification stage of the contract).
- Reach lengths compared with mapped distances & water levels flowing downstream.

- Completeness of structure details, including structure length, skew angle and, if appropriate, the soffit levels.
- Verification that cartographic elements such as land use and fence / wall heights and types on the drawings are present, consistent and correct.
- All data delivered was opened within its appropriate software. For example, an MIKE11 file was opened in the MIKE software to check compatibility as well as data quality.
- Photographs and videos were assessed for quality and labelled correctly.
- The photographs were reviewed for hydraulically significant features (such as overtopping points, walls, trash screens, pipe crossings and blockages) and the section drawing checked to ensure such features were represented
- If any of the above did not fulfill the specified deliverables then it was returned to the surveyor for correction.

All survey data used within each AFA/Model are listed withunder Chapter 4, including digital data folder structure, file names, folder references; any survey issues identified (survey queries) and details of survey query resolution. The details are provided under the relevant AFA/Model withunder Chapter 4 (Sections refer 4.1.2 to 4.9.2, Item (8) respectively for each of the 9 AFAs). In cases where the response to the survey query form was not sufficient to remove any uncertainty with the survey data, it was disregarded from the Study, as detailed under Chapter 4.

Digital Survey Data is also provided as an accompaniment to this report.

Raw survey data has not been converted for the purposes of the CFRAM Study since its provision was already in the format compatible with direct import to hydraulic modelling software.

2.3 DEFENCE ASSET DATABASE

Known flood defence assets within UoM 06 were identified within the tender brief and reported in the Inception Report. The geometric survey of these assets, along with the identification and geometric survey of additional flood defence assets, was a requirement of the UoM 06 channel and cross section survey contract.

On receipt of the survey contract deliverables in mid 2013, RPS extracted the identified assets and circulated mapping and shapefiles to the North Western - Neagh Bann CFRAM Study Progress Group Local Authorities/Regional the OPW representatives within UoM 06. Any further confirmation of the assets received, informed the scope of the condition survey and subsequent defended/undefended model analysis.

Through a process of ongoing engagement with these bodies, a number of additional assets were identified and geometric data collected for these either under the original UoM 06 Survey Contract or by a subsequent infill survey, the contract for which was awarded in May 2014.

Following discussions via the Floods Directive National Technical Coordination Group, the OPW confirmed a CFRAM Defence Asset Database spreadsheet storage format on 9 December 2013. RPS are populated this format with the condition survey, which commenced in the first quarter of 2014 following project level trialling with the OPW CFRAM representatives.

Table 2.1: Flood Defence Assets identified for UoM 06

Location	AFA/ HPW	Structural Form	Identification Stage
River Glyde / River Dee, Annagassan	Annagassan	Embankments	Inception
Belurgan, Dundalk Harbour	Dundalk	Embankments	Inception
Carlingford	Carlingford	Wall	Surveys
Ballymascanlan	Dundalk	Embankment	Surveys
Marsh North, Dundalk Harbour	Dundalk	Embankment	Surveys
Bay Estate	Dundalk	Embankment	Surveys
Blackrock	Blackrock	Wall	Progress Group Engagement

2.4 LAND USE DATA

The Environmental Protection Agency (EPA) GIS Dataset "Coordination of Information on the Environment" known as CORINE was provided at the project outset (7th June 2011 from the OPW) for the most recent version in 2006. The CORINE Land Cover (CLC) is a map of environmental landscape based on interpretation of satellite images. There are five broad levels of land use classification:

1. Artificial Surfaces
2. Agricultural Areas
3. Forest and semi-natural areas
4. Wetlands
5. Water Bodies

These categories are further broken down into 44 classes of specific land use and were provided as a GIS polygon shapefile covering the North Western - Neagh Bann CFRAM Study area. This data was

used in the hydraulic modelling phase to define catchment roughness parameters as detailed in Section 3.5.

3 METHOD STATEMENT

3.1 INTRODUCTION

Hydraulic analysis is a critical part of a CFRAM study. The objective of hydraulic analysis is to gain a detailed understanding of the Study area's flood response and mechanisms to assess both flood risk and determine flood risk management solutions. The accuracy of the models representing existing conditions in terms of flood level, depth, extent and flow velocity allows the possible benefits of flood options to be meaningfully assessed, allowing the appropriate actions/decisions to be taken. To achieve such accuracy; detailed hydraulic modelling analysis of historic flood events, and estimation of design and future flood level, depth, velocity and extent conditions, has been undertaken for each AFA. This analysis takes account of factors influencing in-stream flow and water level, such as the effect of lake and floodplain retention and control structures.

The principal modelling software package that has been used is the MIKE FLOOD software shell (refer to Section 3.3), which was developed by the Danish Hydraulics Institute (DHI). This provides the integrated and detailed modelling required at a river basin scale and provides a 1-dimensional/2-dimensional interface for all detailed hydraulic model development. By adopting MIKE FLOOD a series of fully dynamically linked 1-dimensional/2-dimensional models have been developed thereby incorporating a degree of flexibility into the extent of coverage of the 1-dimensional and 2- dimensional elements within each area. The MIKE FLOOD software shell comprises MIKE 11 for 1-dimensional modelling (fluvial applications) and MIKE 21 for 2-dimensional modelling (fluvial and coastal applications), thus enabling seamless integration of fluvial and coastal models in the AFAs for which this is required. MIKE FLOOD software was adopted for use in modelling eight of the nine AFAs in UoM 06.

The second hydraulic modelling software package used is ISIS (refer to Section 3.4), which was developed by CH2M HILL. ISIS 2D has a fully hydrodynamic computational engine designed to work alone or with ISIS 1D, enabling dynamic interaction between 1D and 2D models. 1D and 2D models are linked through shapefiles specifying the model cells in the 2D domain to be linked to 1D model nodes. Models can be linked by water level (levels computed by the 1D model are sent to the 2D model) or by flow (flows computed by the 1D model are sent to the 2D model). These linking methods allow ISIS 1D and ISIS 2D to represent lateral floodplains, a 1D channel running into a 2D estuary, spill over defences, and other representations of river, coastal or floodplain systems. Multiple 2D domains, with different cell sizes, time steps and simulation times can be coupled to a single 1D model to represent different areas of floodplain at different resolutions. ISIS 2D software was used for one AFA in UoM 06.

The subsequent sections of this Chapter describe the overall conceptualised models and detail the key aspects of each modelling software package used, including model inputs, how channel structures are represented and model parameters selected. The integration of hydraulic analysis with previously

undertaken hydrology analysis is also outlined, with AFA/HPW specifics provided where relevant under Chapter 4.

3.2 MODEL CONCEPTUALISATION

The Inception Report, Chapter 5 and the Hydrology Report, Chapters 4 and 6.1 outline the hydraulic model conceptualisation process which resulted in nine hydrodynamic models in total. AFA/HPW specific model conceptualisation, including modelling software used, is detailed under Chapter 4 of this report and summarised in Table 3.1 below.

Table 3.1: UoM 06 Model Conceptualisation

Chapter 4 Reference	AFA/HPW	Fluvial Risk	Coastal Risk	Fluvial Model Software	Coastal Model Software	Comments
4.1	Monaghan	✓	-	MIKE FLOOD	-	-
4.2	Carlingford	✓	✓	MIKE FLOOD		-
4.3	Greenore	✓	✓	MIKE FLOOD		-
4.4	Dundalk and Blackrock South	✓	✓	MIKE FLOOD		-
4.5	Iniskeen	✓	-	MIKE FLOOD	-	-
4.6	Carrickmacross	✓	-	MIKE FLOOD	-	-
4.7	Ardee	✓	-	MIKE FLOOD	-	-
4.8	Annagassan	✓	✓	MIKE FLOOD		-
4.9	Termonfeckin	✓	✓	ISIS 2D		-

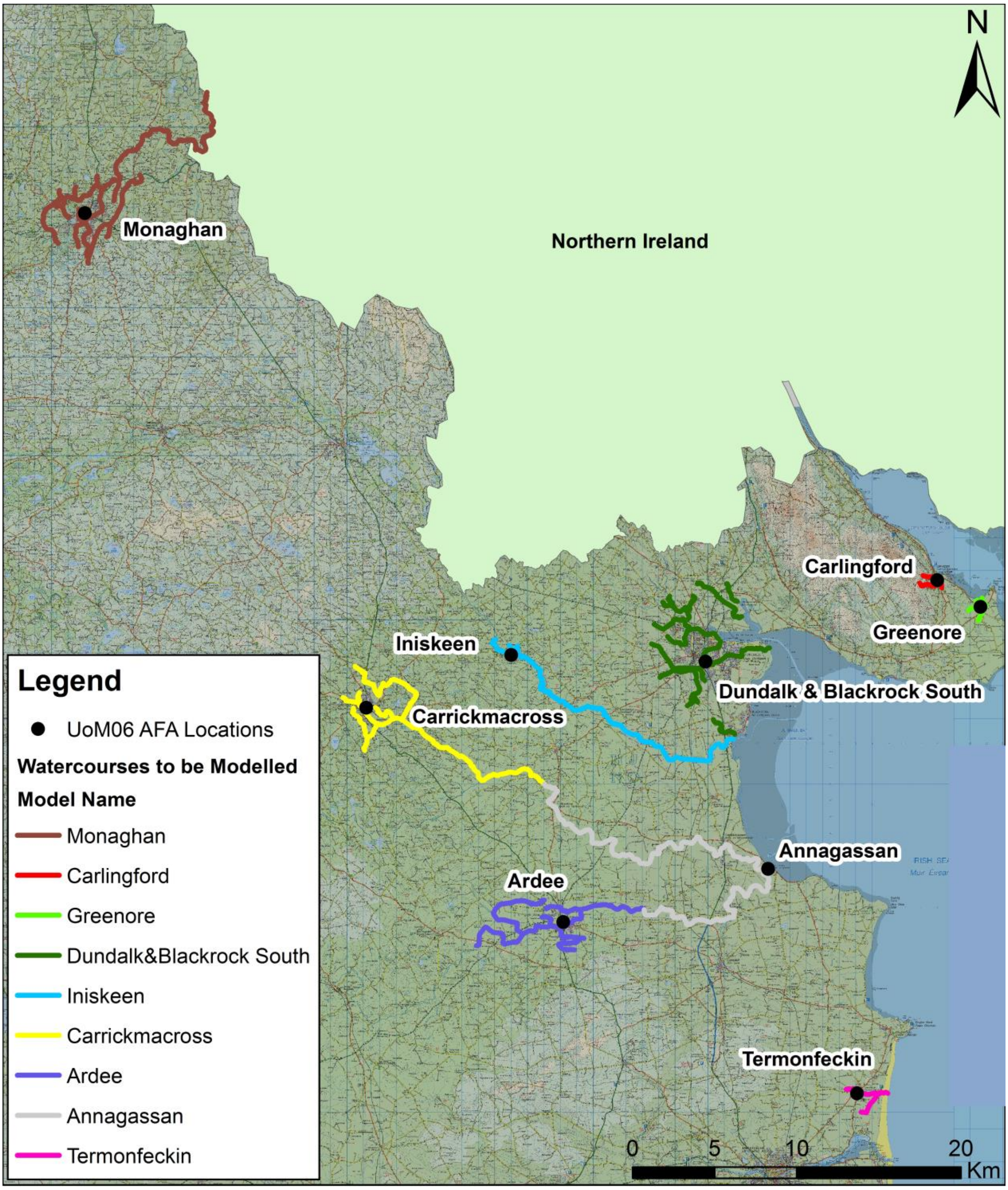

Figure 3.1 illustrates the extent of fluvial models and also the AFA locations.

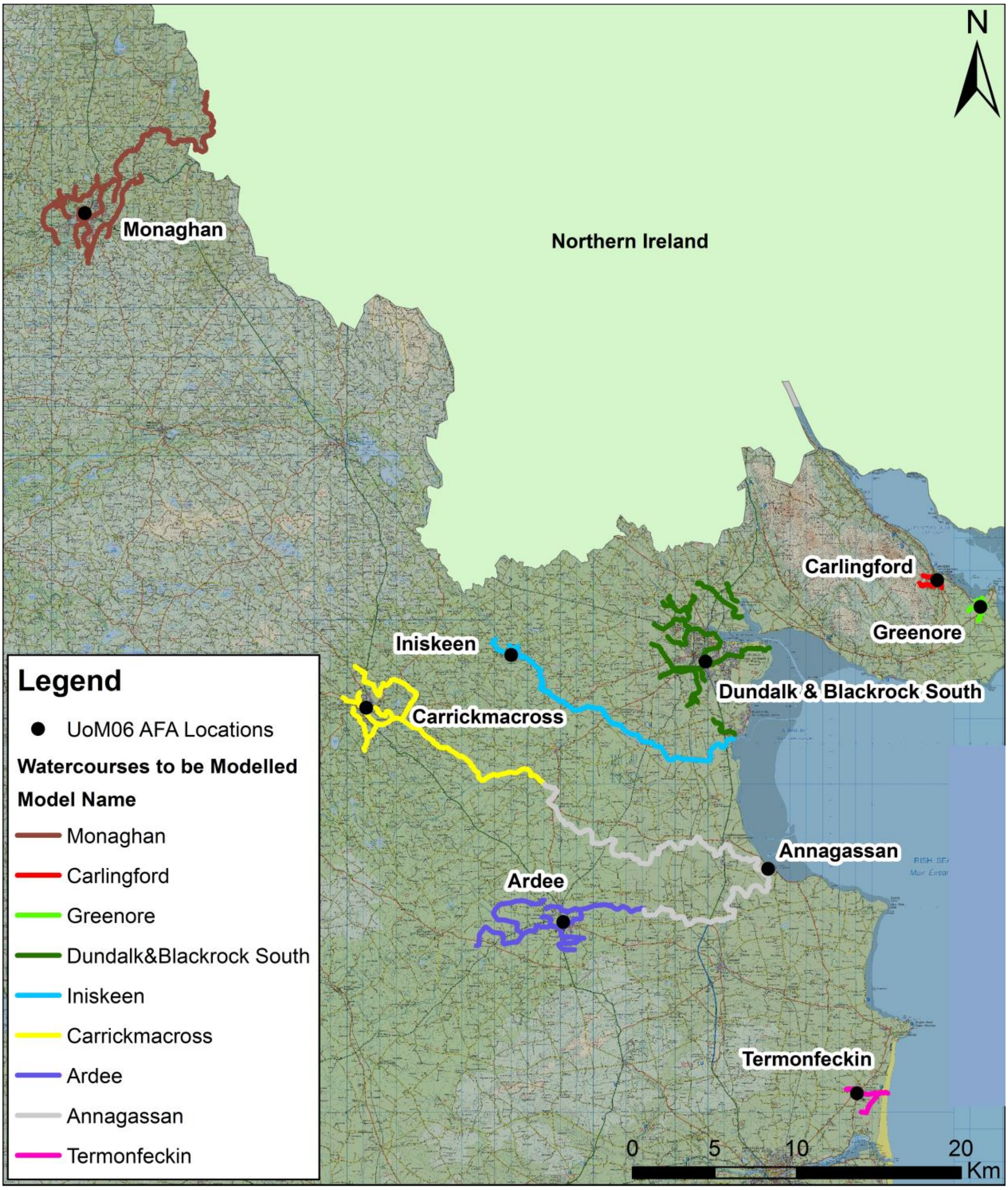

Figure 3.1: UoM 06 Modelled Watercourses and AFAs

3.3 FLUVIAL AND COASTAL MODEL SOFTWARE – MIKE FLOOD

The MIKE FLOOD modelling system (refer to Section 3.1) was utilised for eight models, incorporating eight AFAs, the details of which are included under Chapter 4.

MIKE FLOOD is a software shell comprising the following two components:

- A 1-dimensional river model (MIKE 11 HD) to describe the flow in linear rivers and channels

- A 2-dimensional model (MIKE 21 HD) to describe the free surface flow in the river floodplain.

3.3.1 One Dimensional River Model Inputs (MIKE 11 HD)

The 1-D hydrodynamic models constructed within UoM 06 comprise:

- A Simulation Editor file containing details of the simulation and providing a link to other MIKE 11 editor files. For each hydraulic model created, the simulation editor has the following input files:
    - A Network Editor file (see example given by Figure 3.2) containing the location of the river channel and any branches and details of hydraulic structures on the river (weirs, culverts, bridges etc.) in the tabular view;
    - A Cross-Section Editor file containing all river channel cross-sectional information;
    - A Boundary Editor file (see example given by Figure 3.3) containing all boundary conditions applied to the model including an upstream input discharge hydrograph for each watercourse, a specified downstream boundary and a number of point / distributed discharge hydrographs along the length of the river;
    - A Hydrodynamic Editor file containing details of the hydrodynamic parameters adopted in the simulations.

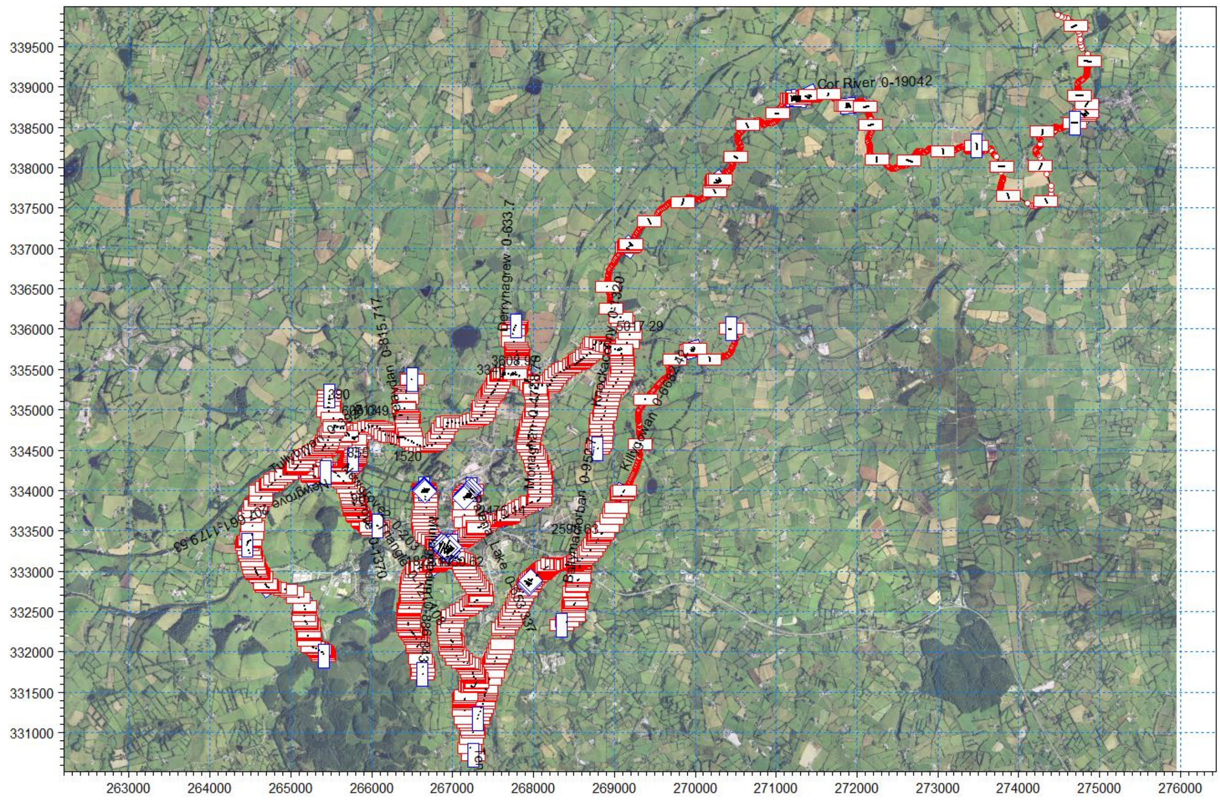

Figure 3.2: Example MIKE 11 Network Editor File

	Boundary Description	Boundary Type	Branch Name	Chainage	Chainage	Gate ID	Boundary ID
1	Open	Inflow	Ballymacforb	0	0		03_341_1_RA
2	Distributed Source	Inflow	Ballymacforb	0	952.7		Top-up flow between 03_341_1_RA & 03_341_Trib_RA
3	Open	Inflow	Cor River	0	0		03_114_3_RA
4	Distributed Source	Inflow	Cor River	0	8179.658		Top-up flow between 03_114_3_RA & 03051_RA
5	Point Source	Inflow	Cor River	13042.529	0		Top-up flow between 03_334_12_RA & 03_425b_Inter_RA
6	Distributed Source	Inflow	Cor River	16059.096	18993		Top-up flow between 03_425b_Inter_RA and 03_399_D_RA
7	Open	Q-h	Cor River	19042.004	0		
8	Open	Inflow	Crove	0	0		03_344_U_RARPS
9	Distributed Source	Inflow	Crove	0	834.547		Top-up flow between 03_344_U_RARPS & 03_344_Int_RARPS
10	Distributed Source	Inflow	Crove	1107	1370		03_344_Trib_RARPS
11	Open	Inflow	Derrynagrew	0	0		03_113_3_RA
12	Distributed Source	Inflow	Derrynagrew	0	523.602		Top-up flow between 03_113_3_RA and 03_113_5_RA
13	Open	Inflow	Killygowan	0	0		03_296_1_U
14	Distributed Source	Inflow	Killygowan	0	6630		Top-up flow between 03_296_1_U & 03_297_7_RA
15	Open	Q-h	Killygowan	6682.421	0		
16	Open	Inflow	Knockaconny	0	0		03_235_U_RARPS
17	Distributed Source	Inflow	Knockaconny	0	1320		Top-up flow between 03_235_U and 03_235_2
18	Open	Inflow	Monaghan	0	0		03_451_1_RARPS
19	Distributed Source	Inflow	Monaghan	0	1829.171		Top-up flow between 03_451_1_RARPS and 03_451_4_RA
20	Distributed Source	Inflow	Monaghan	2046.675	4572.969		Top-up flow between 03_315_trib_RARPS & 03054_RA
21	Open	Inflow	Mullaghadun	0	0		03_315_U_RARPS
22	Distributed Source	Inflow	Mullaghadun	0	886.843		Top-up flow between 03_315_U_RARPS and 03_315_Trib_RARPS
23	Open	Inflow	Newgrove	207.661	0		Newgrove Input
24	Distributed Source	Inflow	Newgrove	207.661	1179.53		Top-up flow between 03_344_Int_RARPS and 03_344_1_RA Newgrove
25	Open	Inflow	Newgrove2	0	0		Top-up flow between 03_344_Int_RARPS and 03_344_1_RA Newgrove2
26	Open	Inflow	Patena_Lake	0	0		03_469_U_RARPS
27	Distributed Source	Inflow	Patena_Lake	0	653.337		Top-up flow between 03_469_U_RARPS & 03_469_Trib_RARPS
28	Open	Inflow	Telaydan	0	0		03_474_4_RA
29	Distributed Source	Inflow	Telaydan	0	608.25		Top-up flow between 03_474_4_RA and 03_474_6_RA
30	Open	Inflow	Tenderages	0	0		03_450_1_RA
31	Distributed Source	Inflow	Tenderages	0	2733.279		Top-up flow between 03_450_1_RA & 03_315_Trib_RARPS
32	Open	Inflow	Triangle	0	0		Triangle
33	Open	Inflow	Tullybryan	0	0		03_184_4_RA
34	Distributed Source	Inflow	Tullybryan	0	3926		Top-up flow between 03_184_4_RA and 03_179_2_RA
35	Point Source	Inflow	Tullybryan	1883.201	0		03_373_5_RA

Figure 3.3: Example Boundary Editor File

3.3.2 Two-dimensional Model Inputs (MIKE 21 HD)

The significant inputs to the 2D- MIKE 21 models are as follows:

- **Topography**

  The topography files used in the MIKE 21 models to define the floodplain are based on the LiDAR and DTM data supplied for the North Western - Neagh Bann CFRAM Study (refer to Section 2.2.1 - 2.2.3, and Chapter 4). A mesh was created from the provided LiDAR data to ensure the accurate assessment of 2D out of bank flow. Building footprints were defined by a GIS file extracted from national vector mapping and the relevant cells blocked out or assigned zero porosity to force water to flow around them. A paper on this topic prepared by Engineers Australia, Water Engineering in February 2012[1] informed the decision on adopting this approach. It is acknowledged that in reality buildings would provide an element of flood storage thus marginally reducing the overall flood extents but there is uncertainty as to the actual volume they would store. Therefore it was considered that preventing flood flows through buildings was a more conservative approach and

[1] Australian Rainfall and Runoff, Revision Project 15, Two Dimensional Simulations in Urban Areas, Representation of Buildings in 2D Numerical Flood Models

would ensure flood extents are not underestimated. Details of the bathymetry files used and how they are applied in each relevant model are provided under Chapter 4.

- **Flooding / Drying Depths**

The MIKE 21 models provide a facility for specifying the depth at which the model cells are identified as wet or dry.

- **Floodplain Resistance**

The resistance or roughness of the floodplain surface can be specified in MIKE 21 as either a Chezy Number or a Manning's Number. For the purposes of this study a Manning's number (M) has been adopted. Manning's 'M' is the inverse of the commonly used Manning's 'n' number, refer to Section 3.5.

3.3.3 In Channel Structures

In-channel structures have been incorporated through the network file (tabular view). The geometry of irregular shaped culverts and bridges are normally defined by 'Cross-Section DB', with regular shaped culverts defined as being circular or rectangular. The 'Cross-Section DB' and Level-Width options have both been employed when installing weirs.

In terms of model stability, the MIKE software developers (DHI) advise that culverts are more stable than bridge structures in MIKE and that culverts (and weirs to allow overtopping of the structure) should be inserted as a proxy for bridges when possible. There is no difference between defining the geometry of the culvert in the model or using a cross-section in the cross-section file (Cross-section DB). DHI also recommend using a series of closed cross-sections to represent long culverts instead of a structure in the network file, as this approach more accurately represents frictional effects.

3.4 FLUVIAL AND COASTAL MODEL SOFTWARE – ISIS

The ISIS modelling system (refer to Section 3.1) was utilised for one model in UoM 06, the details of which are included under Chapter 4.

ISIS is a software shell comprising the following two components:

- A 1-D river model (ISIS) to describe the flow in linear rivers and channels
- A 2-D model (ISIS 2D) to describe the free surface flow in the river floodplain.

3.4.1 One-Dimensional River Model Inputs (ISIS)

The 1-D hydrodynamic model is primarily constructed with an ISIS data file (.DAT) file containing channel cross-sections, structures and boundary conditions. The .DAT file is created using a Graphical User Interface allowing all model components to be geo-referenced and plotted with the assistance of GIS layers (Figure 3.4).

For each hydraulic simulation, the following input files are also utilised:

- An Isis Event File (.IEF) which sets out the simulation parameters used including the .DAT file location, simulation duration, simulation timestep, result file locations. This file also links the .DAT file to the .IIC and IED files as described below
- An Isis Event Data (.IED) file which contains boundary conditions for each specific design event. The data contained within the .IED file will overwrite the original boundary data contained in the .DAT file (Figure 3.5).
- An Isis Initial Conditions (.IIC) file which can be used to set an initial water level at each Isis node at T_0. Initial conditions can alternatively be imported into the .DAT file or taken from an ISIS steady-state results file (.ZZS).

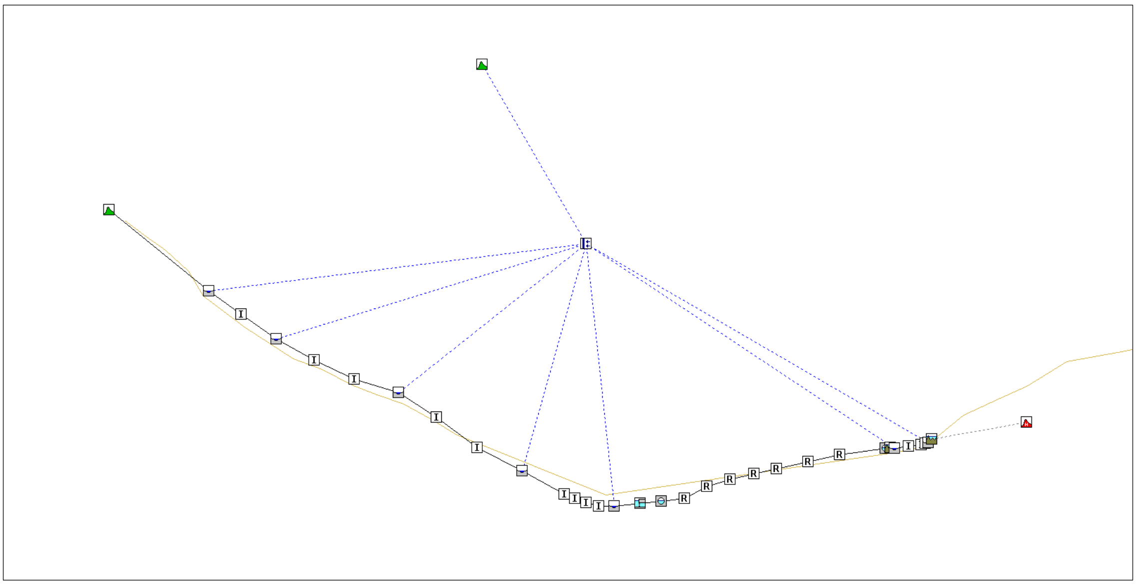

Figure 3.4 Image of .DAT File Shown in GIS Visualiser

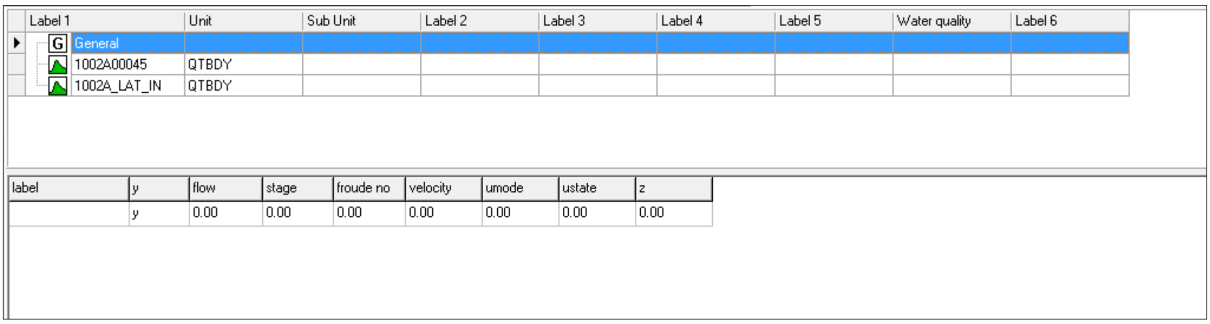

Figure 3.5 Example ISIS .IED File

3.4.2 Two-Dimensional Floodplain Model Inputs (ISIS 2D)

The significant inputs to the ISIS 2D models are as follows:

- **Model Domain Topography**

The topography files used in the ISIS 2D models are based on the LiDAR and DTM data supplied for the North Western - Neagh Bann CFRAM Study and ICPSS (refer to Sections 2.2.1 - 2.2.3, and Chapter 4). A grid mesh was created from the provided LiDAR data to ensure the accurate assessment of 2D out of bank flow. Grid dimensions ranged from 2m to 5m and were chosen based on the complexity of the floodplain topography. Building footprints were defined by a GIS file extracted from national vector mapping and the relevant cells blocked out by setting the bed level to an arbitrarily high value (see Section 3.3.2). Details of the bathymetry files used and how they are applied in each relevant model are provided under Chapter 4.

- **Flooding / Drying Depths**

The ISIS 2D models provide a facility for specifying the depth at which the model cells are identified as wet or dry (refer to Section 3.8).

- **Floodplain Resistance**

The resistance or roughness of the floodplain surface can be specified in ISIS 2D Manning's Number *n* (refer to Section 3.5). These values were sourced from the CORINE land use mapping and used to populate a shape file which is linked to each simulation in the Isis 2D setup file.

3.5 FLUVIAL MODEL PARAMETERS

3.5.1 Roughness Coefficients

Roughness coefficients for cross-sections and structures within 1D river models are taken from the CIRIA (1997) Culvert design guide (see Table 3.2 and Table 3.3). Through site visits, photographs and videos included within the topographical survey information, an appropriate Manning's n value is selected for each cross-section and structure by the modeller. These initial Manning's n values may be amended (within normal bounds) to facilitate achieving model calibration.

Table 3.2: Manning's n Values for Normal Channels and Floodplains (CIRIA 1997)

Type of Channel and Description	Manning's n value		
	Minimum	Normal	Maximum
Natural Streams (top width at flood stage <30m)			
Clean, straight stream			
-full stage, no rifts or deep pools,	0.025	0.030	0.033
-as above, but more stones and weeds.	0.030	0.035	0.040
Clean, winding stream			
-some pools and shoals,	0.033	0.040	0.045
-as above, but some weeds and stones,	0.035	0.045	0.050
-as above, lower stages, more ineffective slopes sections,	0.040	0.048	0.055
-as above but more stones.	0.045	0.050	0.060

Type of Channel and Description	Manning's n value		
	Minimum	Normal	Maximum
Sluggish reaches, weedy deep pools.	0.050	0.070	0.080
Very weedy reaches, deep pools, or floodways with heavy stands of timber and underbrush.	0.070	0.100	0.150
Mountainous streams, no vegetation in channel, banks usually steep, trees and brush along banks submerged at high water levels			
-gravel bed with cobbles and few boulders,	0.030	0.040	0.050
-cobble bed with large boulders.	0.040	0.050	0.070
Floodplains (examples only)			
Pasture, no brush			
-short grass,	0.025	0.030	0.035
-high grass.	0.030	0.035	0.050
Cultivated areas			
-no crop,	0.020	0.030	0.040
-mature row crops,	0.025	0.035	0.045
-mature field crops.	0.030	0.040	0.050
Brush			
-scattered brush, heavy weeds,	0.035	0.050	0.070
-light brush and trees, in winter,	0.035	0.050	0.060
-light brush and trees, in summer,	0.040	0.060	0.080
-medium to dense brush, in winter,	0.045	0.070	0.110
-medium to dense brush, in summer,	0.070	0.100	0.160

Table 3.3: Manning's n Values for Culverts (CIRIA 1997)

Barrel, wall and joint description	Manning's n value		
	Minimum	Normal	Maximum
Concrete pipe			
-good joints, smooth walls	0.011	0.012	0.013
-good joints, rough walls	0.014	0.015	0.016
-poor joints, rough walls	0.016	0.0165	0.017
Concrete box			
-good joints, smooth walls	0.012	0.0135	0.015
-good joints, rough walls	0.014	0.015	0.016
-poor joints, rough walls	0.016	0.017	0.018
Metal pipe			
-68mm x 13mm corrugations	0.022	0.0245	0.027
-100mm x 20mm corrugations	0.022	0.0235	0.025
-127mm x 25mm corrugations	0.025	0.0255	0.026
-153mm x 50mm corrugations	0.033	0.034	0.035
-200mm x 55mm corrugations	0.033	0.035	0.037
-spiral rib metal pipe, good joints	0.012	0.0125	0.013
Concrete			
-trowel finish	0.011	0.0125	0.014
-float finish	0.013	0.0145	0.016
-unfinished	0.014	0.017	0.020

Brick			
-glazed, good condition	0.011	0.014	0.017
-cement, mortar, good condition	0.012	0.015	0.018
-poor condition	0.022	0.026	0.030

The selection of roughness values used for the 2D domains has been based on the CORINE land use dataset (Section 2.5). This is the best land use dataset currently available, covering Ireland at a consistent resolution meaning it is available for all 2D model extents within the CFRAM Study Area. This successfully automated the approach which was applied in the Dodder Pilot CFRAMS and Skibbereen FRAMS. The modeller may edit the roughness coefficients during model calibration where it is deemed necessary and can be justified. The CORINE dataset comprises of 44 different land use types - each of these were reviewed by Senior RPS Modellers and assigned an appropriate Manning's n and M value. The CORINE shapefile incorporating Manning's values was converted allowing it to be imported into the hydraulic modelling software. The values selected are shown in Table 3.4.

Table 3.4: CORINE Description and corresponding Manning's Values

CORINE - Description	Manning's Value	
	n	M
Continuous urban fabric	0.011	91
Discontinuous urban fabric	0.045	22
Industrial and commercial units	0.014	71
Road and rail network	0.013	77
Sea ports	0.014	71
Airports	0.013	77
Mineral extraction sites	0.03	33
Dump	0.05	20
Construction sites	0.04	25
Green urban areas	0.03	33
Sport and leisure facilities	0.03	33
Non-irrigated arable land	0.035	29
Permanently irrigated land	0.03	33
Fruit trees and berries plantations	0.07	14
Pastures	0.035	29
Annual crops associated with permanent crops	0.035	29
Complex cultivation patterns	0.04	25
Land principally occupied by agriculture with significant areas of natural vegetation	0.06	17
Agro-forestries	0.06	17
Broad-leaved forests	0.07	14
Coniferous forests	0.06	17
Mixed forests	0.065	15
Natural grassland	0.035	29
Moors and heathlands	0.045	22
Transitional woodland scrub	0.06	17
Beaches, dunes, sand	0.025	40

CORINE - Description	Manning's Value	
Bare rocks	0.02	50
Sparsely vegetated areas	0.025	40
Burnt areas	0.025	40
Inland marshes	0.025	40
Peat bogs	0.06	17
Salt marshes	0.03	33
Salines	0.03	33
Intertidal flats	0.02	50
Stream courses	0	0
Water bodies	0	0
Coastal lagoons	0	0
Estuaries	0	0
Sea and ocean	0	0

3.5.2 Other Parameters

In MIKE 21, the value for eddy viscosity is normally defined as $0.02(x^{\wedge 2}/T)$ where x represents the mesh resolution and T is the timestep interval. The eddy viscosity value can be amended beyond this calculated value (within normal bounds) in order to improve model stability.

RPS has endeavoured to ascertain the operating controls of dynamic structures, where this is relevant. If this has not been possible, RPS has assumed that all structures are fully open, unless otherwise specified under Chapter 4.

The selection of the timestep varies for each model. For 1D models, the normal range is between 1 second and 5 seconds. Generally, the timestep selected for the 2D model is the same as the 1D model, unless otherwise specified under Chapter 4.

The first MIKE models constructed in UoM 06 used the current software version at that time - MIKE 2011, consequently RPS have constructed all MIKE FLOOD Rectangular mesh models throughout UoM 06 using this software version to maintain consistency. The MIKE FLOOD Flexible mesh model uses the 2012 version of the software and Version 3.7.1 of the ISIS software has been used for the ISIS modelling in UoM 06.

3.6 DEVELOPMENT OF HYDROLOGICAL ANALYSIS

The hydrological analysis for UoM 06 was completed prior to the hydraulic analysis phase of the report and had the overall objective of providing hydrological input files (boundary conditions) in terms of design flows and hydrographs for each hydraulic model, and also flood event calibration data (as derived from hydrometric data recorded for past flood events). The hydrology report documented the methodology, process and outputs and also identified areas where further detail and analysis would be undertaken at the hydraulic analysis stage of the CFRAM Study. The core aspect of this is integration

of hydrology analysis and hydraulic modelling to achieve final design flows as discussed in Section 3.6.1. There are also specific aspects of the hydrology which require further review as part of the hydraulic modelling and these are addressed later in this section.

3.6.1 Integration of Fluvial Hydrological Analysis with Hydraulic Modelling

The hydraulic analysis for each AEP/Model is very much integrated with the fluvial hydrological analysis as outlined in the Hydrology Report and in Figure 3.6. The hydrological analysis produced boundary input and intermediate check files for each hydraulic model. In most cases, these files consisted of design hydrographs for each AEP as defined at every Hydrological Estimation Point (HEP) in the model. Lateral inflow hydrographs were also provided between HEPs to ensure any interim contributing catchment areas were not missed, and to provide a form of flow balancing moving downstream. These hydrographs were simulated in the hydraulic model as the first step in the integration of hydrological and hydraulic analysis.

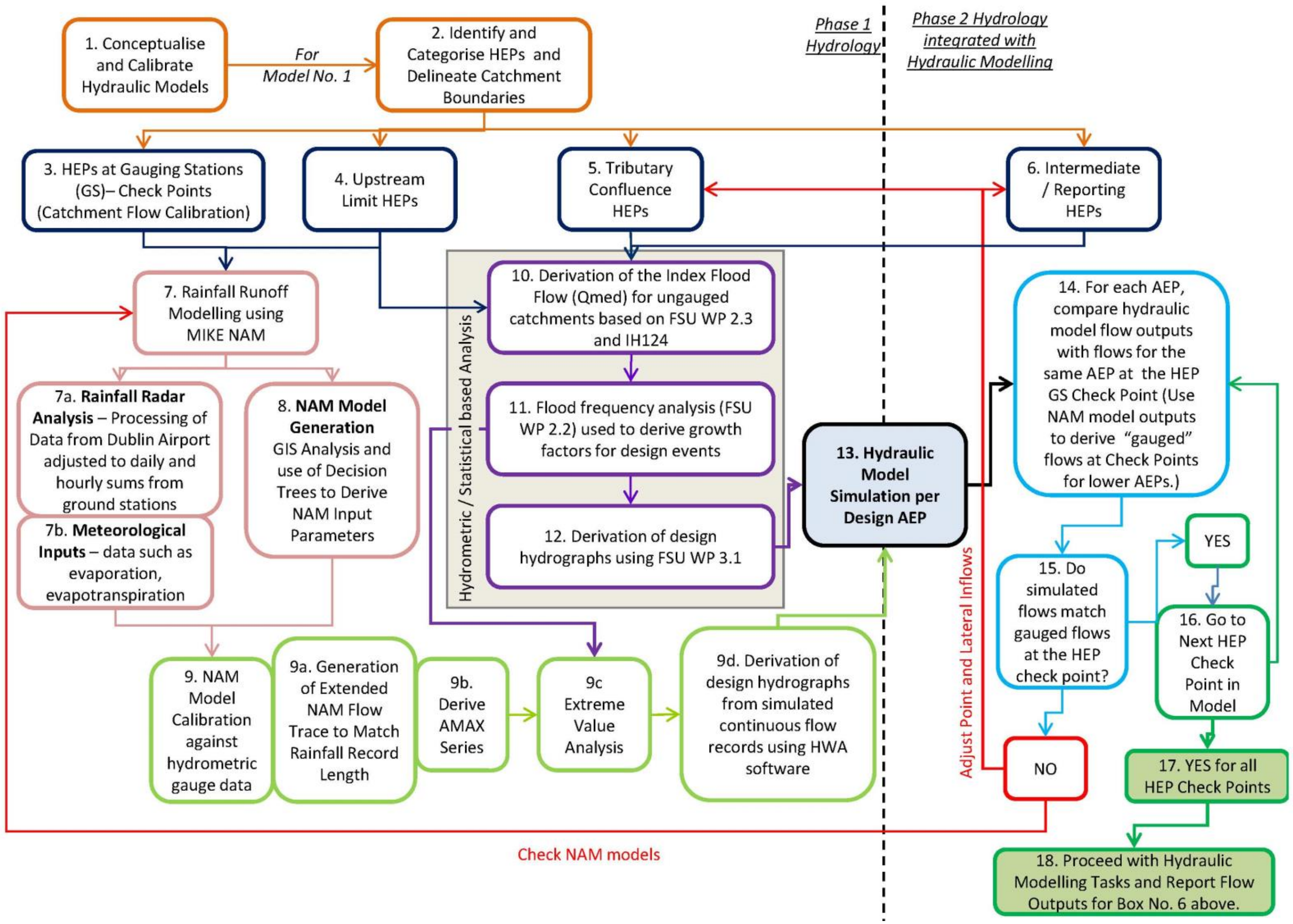

Figure 3.6: Fluvial Hydrology Process Flow Chart (refer to UoM 06 Hydrology Report)

Building on Phase 2 as shown in Figure 3.6, hydrological analysis was revisited using the following hierarchical approach:

1. Fluvial Joint Probability (refer to Hydrology Report Section 6.3.1) - the initial assumption of the same frequency conditions in both watercourses at confluence points is tested against the guidance in FSU WP 3.4 “Guidance for River Basin Modelling” whereby the AEP in the tributary watercourses is reduced based on:
   - gauged data where available on both watercourses or;
   - based on the AREA, FARL and the distance between the centroids of both catchments (see Table 13-1, FSU WP 3.4).
2. Lateral inflows may also be subject to minor adjustment. These flows have been scaled based on the total catchment flow to that point and as such some adjustment may be appropriate.
3. Where the sum of the flows does not achieve the peak flow for the required AEP at the check point then the modeller may refer the model back for hydrology design flow estimation review and / or hydrological re-analysis. Where this is the case the catchment descriptors will initially be checked and further checks on the appropriateness of the adjustment factor and growth factor / pooling group may also be considered.
4. Alternative hydraulic modelling techniques may be considered for urban catchments requiring rainfall based hydrological data input rather than flow based inputs derived from statistical analysis.

The details and justification for this approach are supplied in the Hydrology Report and is referred to here as an example of the integrated approach that has been taken between hydrology and hydraulics.

All cases in which application of the aforementioned hierarchal approach were undertaken as part of the hydraulic analysis phase are detailed withunder Chapter 4 as appropriate.

3.6.2 Hydraulic Model Calibration

The use of flood event data draws on the historic data analysis undertaken at the Inception Stage of the CFRAM Study (refer to Inception Report) whereby key flood events were identified for use in the calibration of each model. The following aspects contributing to model calibration were also discussed in the hydrology report, with further details provided below.

Specific details on the use of past flood event data for model calibration is provided under Chapter 4 per AFA/Model. Generally, the principal model parameters that are reviewed and amended during the model calibration process are identified below:

- Bed and floodplain roughness coefficients;
- Structure roughness and head loss coefficients;
- Timing of hydrographs;

- Magnitude of hydrographs;
- Incorporation of additional survey information (e.g. additional cross-sections or missed structures).

The choice of parameter that should be adjusted in order to calibrate the model will depend on the desired output i.e. whether there is too much or too little flooding in a particular area of the model. The chosen parameter may require adjustment locally at a particular structure or reach of watercourse or globally affecting the entire model. The decision is based on the experience of the modeller and can be an iterative process until selection of the right combination of parameters (within acceptable bounds) generates a flood extent which best represents the flooding mechanisms in the AFA.

3.6.2.1 Rating Review of Hydrometric Stations

In UoM 06 there were three stations specified for rating review through hydraulic modelling as shown in Table 3.5. The full methodology and results and impacts of the rating review analysis are included in the Hydrology Report. From a hydraulic modelling perspective the outcomes of the rating reviews were identified in the Hydrology Report as having a potentially high impact on the associated hydraulic model calibration since this depends on the upper limits of a gauge rating i.e. observed historical flood event flow data. This could be changed based on the results of rating reviews i.e. if significant uncertainty is identified in the current rating and it is deemed appropriate to revise it using the CFRAM Study hydraulic analysis rating curve. Table 3.5 identifies the stations for which significant uncertainty with the current rating was identified by the rating review.

Table 3.5: Hydrometric Station Rating Reviews

Station Number	Station Name	Final Station Rating Quality Classification	AFA/HPW Model	Significant Uncertainty Identified in current rating
06011	Moyles Mill	A1	Iniskeen	No
06021	Mansfieldstown	Not Rated	Annagassan	No
06025	Burley	A1	Ardee	No

As indicated by Table 3.5, no stations to date showed significant uncertainty with the current rating.

3.6.2.2 Use of NAM modelling flow outputs

Full details of the use of hydrological rainfall run-off (NAM modelling) are provided in the Inception and Hydrology Reports. The overall objective was to provide an additional layer of simulated flow data at gauging stations where an augmented AMAX series was of potential benefit to the core statistical based hydrology analysis in determining design flows for each model (refer to Figure 3.6). Another potential benefit of the rainfall runoff models was identified in that a further layer of simulated hydrometric data would be available for calibration of the hydraulic models. Events which may be

outside the continuous flow record period of the gauge would now be available through the simulated time series flow data at hydrometric stations where NAM modelling was undertaken. No continuous level information is available as the models are spatially dimensionless (i.e. they are not hydraulic models with inputted topographical survey information) but the simulated flow information could potentially be used to replicate the recorded flood extents for historic events not previously captured.

This potential benefit was utilised in the hydraulic modelling calibration of the Monaghan AFA as summarised in Table 3.6 and detailed under Chapter 4.

Table 3.6: Use of Simulated Flow Trace (NAM outputs) at Hydrometric Stations for Hydraulic Model Calibration

Hydrometric Station	Model	Simulated Flow Trace used for flood event calibration?
03051 (Faulkland)	Monaghan (1)	Yes

3.6.2.3 Consultation Activities

Consultation activities which occurred from early to late 2015 on the draft flood maps included:

- Consulting with the relevant Local Authority representatives during the development of the draft flood mapping;
- Holding a series of Public Consultation Days, including a dedicated Elected Member briefing session, to outline the flood mapping process and to elicit feedback on the draft flood maps;
- Holding a workshop with the members of the North Western – Neagh Bann CFRAM Study Stakeholder Group to outline the flood mapping process and to elicit feedback on the draft flood maps;
- Uploading the draft flood maps to the project website and inviting feedback on the draft flood maps.

Further details on the above consultation activities are contained within the Draft Flood Mapping Phase Summary Report (IBE0700Rp0016_Mapping Phase Summary Report_D01).

A formal consultation on the draft flood maps was launched by Mr. Simon Harris T.D., Minister of State at the Department of Public Expenditure and Reform with special responsibility for the Office of Public Works, under SI 122 of 2010. This consultation occurred between 20th November 2015 and 23rd December 2015. The draft flood mapping was available for viewing within an online mapping tool and was also put on display at Local Authority offices. The SI consultation provided a mechanism for Technical Objections under SI 122 of 2010.

All of the submissions, observations, comments and technical objections received in relation to the consultations activities described above were taken on board during the finalisation of the flood mapping. Further details on where the submissions received resulted in amendments to the hydraulic analysis are available in Chapter 4.

3.7 FLUVIAL MODEL SENSITIVITY

Sensitivity tests have been conducted for each model. The parameters selected were dependent on the specific model but generally included those listed below. The model output for each sensitivity model simulation is compared with the verified model, with a discussion on the sensitivity of the selected parameter given in the relevant section of Chapter 4:

- roughness coefficients
- 2D domain grid cell size
- critical structure coefficients
- flow inputs
- operation of dynamic structures

The suggested amendments to each parameter detailed in 'Guidance Note 22 - Sensitivity Analysis and Uncertainty' will be considered when conducting the sensitivity tests, although these may be amended for particular models where appropriate. Further details are given under Chapter 4.

3.8 COASTAL MODELLING

In order to facilitate the computational modelling for those AFAs located within close proximity to the coast, a similar approach was taken as for the inland, fluvially-dominated areas. However, some major differences included the addition of coastal boundaries and coastal bathymetry, the use of flexible mesh where necessary and the consideration of joint probability between fluvial and tidal components.

Each coastal area was reviewed in order to ascertain if the tidal component was influential to the cause of flooding in the area. Where this was the case, a decision was made whether to utilise flexible or rectangular mesh, depending on the topography of the area and the extents and position of those areas likely to flood. In order to make this judgement, a thorough review of available LiDAR information was undertaken. Taking into account the worst possible coastal water level to be considered within this study, the 0.1% AEP HEFS, those coastal areas with elevations below the corresponding water level, with a direct flood path from the sea, would most likely be coastally inundated. Areas where coastal inundation is an issue were modelled using a combination of flexible and rectangular mesh approaches for MIKE models, with the flexible mesh approach adopted in areas with extensive coastal floodplains due to the ability to vary the mesh size across the domain. A rectangular mesh approach was deemed appropriate for use with the ISIS models.

A fully functioning tidal model was developed for each relevant AFA. It was important to ensure a representative tidal model was achieved, with water moving freely and realistically throughout the model domain. The floodplain and buildings were also included in the model.

A bed roughness map was produced for all models, using the CORINE dataset. Coastal bed resistance values were taken as a Manning's M value of 30m(1/3)/s, which was adjusted in the calibration and sensitivity analysis as necessary. Flood defence assets, where they have been identified (see Table 2.1), were included in the model mesh.

3.8.1 Coastal Model Boundaries

Model boundaries were established on an individual basis for each model and are detailed under Chapter 4. In general, boundaries were located in an appropriate position offshore in areas of similar topography and suitable water depth. The boundaries were representative of extreme total water levels derived under the ICPSS, with a range of suitable AEPs available. The ICPSS water levels are total water levels, comprising tidal and surge components which together yield a joint probability event of a particular AEP. These vary around the coastline and are specific to each AFA, as detailed under Chapter 4.

Using information from the Admiralty Tide Tables, RPS established a tidal water level approaching Mean High Water Springs (MHWS) which was representative for each individual area and from this deduced the resultant magnitude of the surge component required to produce a total water level for the relevant AEP.

Temporally varying water levels have been used to represent the coastal boundaries in all relevant AFAs throughout this study. The inclusion of a temporal element within any detailed assessment of tidal flood risk is a very important consideration due to the relatively rapid variation in even extreme tidal events associated with the normal astronomical tidal cycle. In general, this limits the duration of defence exposure and over-topping and consequently is an important consideration in establishing the volume of water that can enter vulnerable areas. RPS' experience with detailed modelling of coastal flooding has indicated that it is seldom sufficient to simply model a single tidal cycle, as extreme tidal surges often persist over multiple tidal cycles. Consequently the most onerous tidal flooding is normally a result of the accumulation of flood waters entering the area over multiple tidal cycles.

In some complex cases, and where appropriate, tidal boundary profiles were extracted from the RPS Irish Surge and Tidal Model (ISTM) in order to represent a realistic tidal regime of the area. In other cases, the position of the boundaries and their associated bathymetry and tidal regime facilitated a more simplified approach, which involved scaling a sine curve to the appropriate magnitude and frequency to determine the tidal component of the boundary.

Using information from the ISTM, as well as observed extreme events where available, RPS has established that a typical profile of a surge event could be adequately represented in this study by a

positive sine curve of 48 hours duration. Each sine curve was scaled appropriately to achieve a surge residual of the relevant magnitude.

The relevant tidal curve was combined with the appropriate residual surge profile to obtain the total combined water level time series as required for the relevant AEPs. It was assumed that the peak of the surge would coincide with the peak of the tide at the boundary locations.

Each time series includes a number of tidal cycles, with one preceding the onset of the surge event to assist in developing stable conditions within the models, prior to modelling the onset and progression of inundation during the surge event.

3.8.2 Coastal Modelling Software

The computational modelling of coastal flooding in UoM 06 was undertaken using MIKE FLOOD and ISIS 2D, as discussed in Sections 3.1 to 3.4. To adequately represent the variable bathymetry and topography, the model mesh for each flexible mesh AFA was generated and refined in regions of most importance to achieve satisfactory model performance. The flexible mesh technology allowed the size of the computational cells to vary across the domain of each model, allowing smaller cells of circa 5 metres to be positioned in areas of rapidly changing bathymetry, such as offshore banks and channels, along with detailed areas of topography. Smaller cells were vital in depicting flood paths between buildings. Larger cells in the order of 100 to 200 metres were used in areas of more consistent bathymetry, such as agricultural land, mud flats and the open sea. In less complex/extensive area a fine grid rectangular mesh (2-5m resolution) was employed.

3.8.3 Coastal Simulations, Joint Probability and Sensitivity

Upon development of a completed and successfully calibrated model, relevant simulations were undertaken in order to determine the worst case scenario flooding for each AEP.

As a starting point, RPS reviewed both coastal dominated and fluvial dominated scenarios for each AFA, combining low probability events from one source, with a more frequently occurring 50% AEP event from the other. It was assumed that in order for such an event to be extreme, the likelihood of at least some activity from the other source was high, before joint probability was considered further.

As such, coastal events of 10%, 0.5% and 0.1% AEP were combined with a fluvial event of 50% AEP in order to produce joint return periods of 10%, 0.5% and 0.1% AEP for a coastal dominated scenario.

Conversely, fluvial events of 10%, 1% and 0.1% AEP were combined with a coastal event of 50% AEP for joint return periods of 10%, 1% and 0.1% AEP for a fluvial dominated scenario.

Where there were significant areas of overlap between these outputs, and where other historical information, PFRA data and ICPSS flood extents indicated a relationship, the requirement for joint probability analysis was considered during a screening analysis, as outlined in the Hydrology Report. However, due to the lack of available historical gauge information, a simple analytical approach was

generally used in determining the correlation and joint probability for relevant AFAs, as outlined in the South Eastern CFRAM Study NTCG GN20 Joint Probability Guidance. Where necessary, further simulations were set up to determine flood extents for medium/medium events, where flooding was not dominated solely by fluvial or coastal events, but was a combination of less extreme events from both sources for a given joint AEP.

Sensitivity tests were undertaken for the principal parameters used within the model to identify the degree of variability within the model output associated with the model inputs. This included variation in the joint probability and temporal variations, along with parameters such as eddy viscosity and bed resistance. In some AFAs, relative timing between fluvial and coastal peaks was critical in the determination of flood extents, and in general it was assumed the events from both sources would peak together at the location affected most by both fluvial and coastal flooding. As such, timings were adjusted and using an iterative approach, the worst case flood outlines, for a particular combination of events, were established.

3.8.4 Wave Overtopping

Where the OPW has provided joint return period combinations of wave heights and water levels under the CFRAM programme in accordance with Section 2.26 of the Stage II Project Brief and suitable details of the relevant structures are available, either as output of the CFRAM surveys or from the data collection exercise, RPS has assessed the potential for wave overtopping leading to coastal flooding. In terms of UoM 06, the AFAs for which the OPW has supplied wave/water level data are Dundalk, Blackrock South, Annagassan, Termonfeckin, and Carlingford.

The "*Wave Overtopping of Sea Defences and Related Structures - Assessment Manual*", published in 2007, has an author team comprising experts in the field of overtopping from several European countries. This "European Overtopping Manual" presents the latest techniques and approved methods for establishing overtopping hazards and flooding for an extensive range of structure types. Currently this approach is recognised within Europe as best practice on the analysis and/or prediction of wave overtopping for flood defences attacked by wave action.

In parallel with this manual, an online Calculation Tool (EurOtop) has been developed to assist the user through a series of steps to establish overtopping predictions for embankments, dikes, rubble mound structures and vertical structures. The following features are available via the online tool:

- Calculation of mean overtopping discharge, overtopping volumes and number of overtopping waves.
- Calculation flow velocity and flow depths of waves overtopping sloping structures.
- Provision of information and support for required data input.

In order to determine the flood hazard associated with overtopping RPS have calculated overtopping rates for relevant coastal structures under a range of combined tidal levels and wave heights of known

joint return period using the EurOtop application. The results of this exercise enables the critical structure/overtopping rate/event combination for the frontage to be identified.

The temporal variation in overtopping rate for the frontage is subsequently determined using EurOtop to analyse the performance of the critical structure, under the critical wave conditions and a range of tidal levels associated with a generic storm profile derived from a combination of the normal astronomical tidal profile and an appropriate sinusoidal surge profile with a duration of 48 hours. The instantaneous overtopping rates resulting from this analysis were combined to create boundary "hydrographs" that can be applied to the coastal flood models at the locations of the overtopping defences to facilitate simulation of the flood pathways and flood extents resulting from overtopping of the defences. The results of the coastal modelling were then combined with the output of the direct tidal inundation mapping to establish the coastal flood hazard maps.

It should be noted that the methods and tools provided by EurOtop assist in establishing preliminary predictions for overtopping discharges for the structure types discussed in the EurOtop manual. They are not intended to be used for detailed design or assessment of structures subject to wave overtopping. It is recommended that detailed design or assessment of any structure should use hydraulic and physical model testing to verify the overtopping discharges where this is practicable.

3.9 FUTURE SCENARIOS

The OPW does not have a specific policy for the design of flood relief schemes but has produced a draft guidance note 'Assessment of Potential Future Scenarios for Flood Risk Management' (The OPW, 2009). The document gives guidance on the allowances for future scenarios based on climate change (including allowing for the isostatic movement of the earth's crust), urbanisation and afforestation. Table 1 from the guidance has been adapted for the purposes of this study to take into account catchment specific effects which were used in the hydrology analysis as the basis for the design flow adjustment for the mid range (MRFS) and high end (HEFS) future scenarios (refer to Hydrology Report, Chapter 8).

The future potential changes which may affect the outputs of the CFRAM Study were identified and described in the Hydrology Report under the following headings:

- Climate Change
- Afforestation
- Land Use and Urbanisation
- Arterial Drainage
- Geo-morphology

The allowances applied to design flows and coastal boundary conditions for climate change (extreme rainfall depths, flood flows and mean sea level rise); urbanisation; and afforestation are shown in Table 3.7 and detailed in the Hydrology Report.

Table 3.7: UoM 06 Allowances for Future Scenarios (100 year time horizon)

	MRFS	HEFS
Extreme Rainfall Depths	+ 20%	+ 30%
Flood Flows	+ 20%	+ 30%
Mean Sea Level Rise	+ 500mm	+ 1000mm
Urbanisation HA03	UAF[1] of 1.15 Urban W.C. UAF[2] of 1.412	UAF[1] of 1.7 Urban W.C. UAF[2] of 1.744
Urbanisation HA06	UAF[1] of 1.16 Urban W.C. UAF[2] of 1.412	UAF[1] of 1.77 Urban W.C. UAF[2] of 1.744
Afforestation	-	-

Note 1: UAF (Urban Adjustment Factor) applied to 'greenfield' flow estimates.

Note 2: UAF (Urban Adjustment Factor) for small urban tributaries within AFA extents assume 85% urbanisation. Assessed on a case by case basis.

The climate change allowances are applied to all models. Urbanisation allowances are applied on a case by case basis as required, the factors themselves having been derived during the hydrology analysis by looking at historic urbanisation growth indicators and estimating appropriate growth factors for MRFS and HEFS. The outputs of future scenarios modelling for each AFA/HPW are detailed under Chapter 4.

The effect of arterial drainage within UoM 06 relates to the catchments of Monaghan, Carrickmacross, Annagassan and Ardee. The Glyde and Dee Arterial Drainage Scheme took place between 1950 and 1957 and was a pilot drainage scheme implemented shortly after the 1945 Arterial Drainage Act. The Monaghan Blackwater Scheme was a smaller, more recent scheme that took place between 1984 and 1992.

In terms of sedimentation of rivers, the initial schemes have had the long term effect of making river courses more susceptible to bed and bank erosion in high flow conditions and resulting siltation. This was due to the removal of natural gravels and bank vegetation. However this impact is more of a consideration in the Glyde and Dee Scheme since it was one of the first to be carried out. Environmental practices evolved over time such that the Monaghan Blackwater Scheme is likely to have had less impact in this regard.

Maintenance activities are required to maintain channel capacity by removing silt and debris build up, typically every six years. Maintenance works in itself can be a source of sediment loss if bank vegetation and river buffer zones are not protected. However comprehensive environmental drainage maintenance practices have been employed in light of the Water Framework Directive and other related legislation, which minimise the risk of sediment loss whilst still maintaining channel conveyance capacity from a flood risk perspective.

In terms of the modelled watercourses, the recently acquired channel cross section survey data will reflect the current status of the watercourses in terms of siltation based on the measurements taken for modelling purposes. Therefore the models will reflect present day conditions as closely as possible.

Geomorphological changes ultimately apply to the performance of flood risk management options and as such, this will be considered further and reported on in the next stage of the CFRAM Study.

3.10 APPROACH TO FLOOD MAPPING

Flood mapping utilises ArcGIS to present the results of the hydrodynamic models on background mapping and to derive a series of flood hazard maps in support of the CFRAM Study. ArcGIS version 10.0 is utilised for the production of all AFA mapping. Before commencing the mapping, the raw outputs of the models are checked and cleaned to remove outliers and islands which are not connected to the fluvial or coastal flooding mechanisms.

The approach for the generation of flood maps from the output files of MIKE FLOOD Classic Grid (rectangular mesh) models involves the use of the Statistics tool from the MIKE Zero toolbox. The maximum parameter (e.g. depth) is extracted from the dfs2 results file generated by populating the 'Maps' tab within the HD Parameters file in MIKE11. This file covers both the 1D and 2D model domains. The maximum dfs2 output file is opened in ArcGIS (using a dfs2 Plug-in) and converted to a grid raster format which is reclassified as a singularity and subsequently converted to a shapefile showing the flood extent.

For MIKE FLOOD Flexible Mesh models, the above process is repeated but the 'Maps' results file covers the 1D domain model domain only. A separate process using Data Extraction FM (within MIKE Zero) is required to extract the maximum parameter from the flexible mesh results output (dfsu file). The Mike2Shp tool in the MIKE Zero toolbox is used to convert this file to a shape file, which gives the maximum level within each element of the mesh for that model simulation. It is edited in ArcGIS to remove values below 0.02m to provide the best representation of the flood extent. A raster file is created based on the maximum levels to generate a depth map of the floodplain. Both results files described above are then combined to generate the flood map covering both the 1D and 2D model domains.

The same approach is used to generate flood velocity maps as all of the required information is contained within the model output files. MIKE ECOLab is used to generate the risk to life maps, based on the maximum velocity and depth reached within the model results file.

For the generation of flood maps from the output files of ISIS models, this entails exporting the model results to a raster dataset of the 2D extents. For the 1D (river channel) element of ISIS models, the outputs are presented in a csv format, which are then referenced to the corresponding cross-sections in ArcGIS. Each cross-section contains the maximum level reached during the model simulation - these levels are interpolated to generate an elevation surface shapefile for the 1D channel. The shapefile is then converted to a surface raster. The DTM information is subtracted from the elevation surface files to generate the flood depth information. The 1D and 2D raster files are combined to generate a complete extent of the floodplain from which a shapefile is produced. The shapefile is overlaid on background mapping, to produce flood extents maps. The same approach is used to generate flood velocity and risk to life maps as all of the required information is contained within the model output files.

The map is set at the appropriate scale (1:5,000 or 1:25,000 for HPW and MPW respectively), additional information added (such as the river centre line) and set within the completed title block. A pdf of the map is created to ensure the map is in print-ready format.

3.11 ASSUMPTIONS, LIMITATIONS AND UNCERTAINTY

There are inherent assumptions, limitations and uncertainty associated with hydraulic modelling which are beyond the scope of this report. The assumptions, limitations and uncertainty which are specific to each individual model are discussed in detail under Chapter 4. Each issue is discussed, with the requirement for the assumption justified. The issues addressed will include:

- schematisation decisions regarding out-of-bank flow routes;
- culvert/bridge schematisation (including skew angle considerations);
- sweetening flow assumptions;
- comments and notes throughout to reflect data sources; changes to parameters from default;
- explanation of parameters used that are outside of the expected ranges; and
- any other atypical assumptions made.

4 MODEL SPECIFIC DETAILS

The specific details of each model can be found in a separate report - Table 4.1 gives the report reference for each of the AFAs in UoM 06.

Table 4.1: UoM 06 Model Names and Report References

Report Reference	Model Name
4.1	Monaghan
4.2	Iniskeen
4.3	Carrickmacross
4.4	Ardee
4.5	Carlingford
4.6	Greenore
4.7	Dundalk and Blackrock South
4.8	Annagassan
4.9	Termonfeckin

5 CONCLUSIONS AND RECOMMENDATIONS

To be completed in F03 version of report

6 REFERENCES

1. EC Directive on the Assessment and Management of Flood Risks (2007/60/EC)

2. S.I. No. 122/2010 - European Communities (Assessment and Management of Flood Risks) Regulations 2010

3. North Western - Neagh Bann CFRAM Study, UoM 01 Inception Report, IBE0700Rp0002 (RPS, 2013)

4. North Western - Neagh Bann CFRAM Study, UoM 01 Hydrology Report, IBE0700Rp0006 (RPS, 2014)

5. Flood Studies Update Programme – Work Package 1.2 – Estimation of Point Rainfall Frequencies – prepared by Met Eireann for Office of Public Works (October 2007)

6. Engineers Australia, Australian Rainfall and Runoff, Revision Project 15, Two Dimensional Simulations in Urban Areas, Representation of Buildings in 2D Numerical Flood Models, (Water Research Laboratory, University of New South Wales, 2012)

7. Flood Studies Update Programme – Work Package 3.4 – Guidance for River Basin Modelling – prepared by JBA for Office of Public Works (May 2010)

8. Culvert Design and Operation Guide - R168 (CIRIA, 1997)

9. EurOtop (2007). Wave Overtopping of Sea Defences and Related Structures – Assessment Manual. Eds. Pullen, T., N.W.H Allsop, T. Bruce, , A. Kortenhaus, H. Schüttrumpf & J.W. van der Meer. www.overtopping-manual.com.