Fingal East Meath Flood Risk Assessment and Management Study

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Executive Summary

Fingal County Council (FCC), in conjunction with Meath County Council (MCC) and the Office of Public Works (OPW), are undertaking a flood risk assessment and management study in Fingal and East Meath – the Fingal East Meath Flood Risk Assessment and Management Study (FEM FRAMS). Halcrow Barry (HB) was commissioned to carry out the work on behalf of FCC/MCC/OPW. The main report from this study – a Flood Risk Management Plan – will identify a programme of prioritised studies, actions and works to manage flood risk in the Fingal and East Meath (FEM) study area.

This Hydrology Report, together with the Preliminary Hydrology Report published in February 2009, details the hydrological assessment that has been undertaken for this study with the objective of determining hydrological inputs for the 23 rivers and streams in the study area that are to be modelled, for specific design events and future scenarios. The hydrology is based on a review and analysis of historic flood information and use of meteorological and hydrometric records. The Flood Studies Report (FSR), Flood Estimation Handbook (FEH) and the Irish Flood Studies Update (FSU) methodologies have been used to enable the determination of design hydrological inputs which also consider potential future catchment changes likely to influence flood risk.

The analysis presented in this report is concerned with the estimation of extreme flows, which will form the basis for subsequent flood level and mapping stages of FEM FRAMS. To distribute these flows along the river reach, the HPWs (High Priority Watercourses) and MPWs (Medium Priority Watercourses) sections of the 23 rivers and streams that are to be modelled, have been further sub-divided into a total of 270 sub-catchments. Catchment characteristics of these sub-catchments have been extracted using GIS automation tools aided by manual checking. Design inflows at these sub-catchments are calculated using the catchment characteristics, FSU-based rainfall inputs and applying the FSSR 16 and IOH 124 unit hydrograph methods. The total routed inflows from all the upstream sub-catchments at the gauging stations will be reconciled with the statistical method estimated design floods at the gauging stations using iterative simulations in the river hydraulic models.

Hydraulic model calibration and verification events have been identified by reviewing the information on historic floods in the study area including photographs of flood events or their aftermaths. It should also be noted that most of the hydrometric stations in the study area were inoperational between 1995 and 2001 and thus the recent flooding events do not have corresponding hydrometric information. This meant that calibration of only three river hydraulic models out of the total 23 river and stream models was possible. To assist in the future model calibration and flood forecasting in the rivers, Halcrow Barry has developed a priority list of hydrometric gauging stations that should be installed or re-activated in the catchment.

The FEM FRAM study will identify both the existing risk and potential future risk of flooding in the study area. There are a number of drivers that can influence future flood risk in the study area, the main drivers have been identified as being climate change and increasing urbanisation. These drivers have been extensively investigated and two future flood risk management scenarios have been proposed, a Mid Range Future Scenario and a High End Future Scenario. The outputs from this hydrological assessment will inform the subsequent stages of this study and, in particular, the hydraulic modelling and flood mapping stages. Knowledge of the hydrological processes and historic flooding gained from this work will support the decision making process for the flood risk management options.

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1. Introduction

1.1 Background

The Fingal and East Meath area has suffered significant and frequent flooding over the last 23 years: the events of August 1986 (Hurricane Charlie), November 2000 and November 2002 all resulted in considerable flood damage in the area. The highest recorded tidal levels in Dublin Bay occurred in February 2002, resulting in tidal damage to properties along the Fingal and Meath coastline. More recently, surface water flooding in the summer of 2008 caused damage to property and disruption to the road network.

Fingal County Council (FCC) along with project partners Meath County Council (MCC) and the Office of Public Works (OPW) have recognised the high levels of existing flood risk in Fingal and East Meath. This, combined with the significant development pressure associated with Ireland's fastest developing area and predicted changes in climate, are likely to increase the flood risk in the future. To address these issues, FCC, MCC and the OPW have commissioned a catchment-based flood risk assessment and management study, named, the Fingal East Meath Flood Risk Assessment and Management Study or FEM FRAMS for short.

The FEM FRAM study area constitutes the Irish Hydrometric Area 08 and some of Area 09. It is approximately 772km^2 in plan area consisting of 24 rivers and streams and their catchments within Fingal and East Meath, and the coast. The Mornington River is the subject of a separate detailed flood alleviation scheme and the results and recommendations from that study will be incorporated into the FEM FRAMS. Thus the present study involves modelling of 23 rivers and streams in the study area.

The principal output from this study, a Flood Risk Management Plan (FRMP), will identify a programme of prioritised studies, actions and works (both structural and non-structural) to manage the flood risk in the Fingal and East Meath (FEM) study area in the long-term, and make recommendations in relation to appropriate development planning.

The FEM FRAMS area is shown in Figure 1-1 and a more detailed map of the study catchment area is presented in Figure 1 in Appendix A.

The FEM FRAM study is one of the four principal flood risk management studies currently underway in Ireland to meet the requirements of the EU Floods Directive. The other three catchment FRAMS are the Lee Catchment (Cork), the River Suir (Tipperary, Kilkenny, Waterford and Limerick) and the River Dodder (Dublin).

Figure 1-1: FEM FRAM Study Area

1.2 General description of the study area

The Fingal East Meath study area comprises a group of river catchments and coastline. The study area is bounded by the River Boyne catchment area to the north and west, the Tolka and Santry River catchments to the south, and by the Irish Sea to the east.

The topography of the study area is generally low undulating land intersected by 22 named rivers, 2 small unnamed watercourses and 3 estuaries. For identification purpose, the unnamed streams in the study area are also assigned with a unique name. Table 1-1 lists all the rivers, streams and estuaries in the study area and Figure 1 in Appendix A shows the catchment area of the rivers and streams. Description of the rivers and streams in the FEM FRAM study area is presented in Chapter 3 of Preliminary Hydrology Report.

Table 1-1: Rivers and streams relevant to the study

Rivers, Streams and Estuaries relevant to the study		
Mayne River (MAY)	Baleally Stream (BAY)	Balbriggan North Stream (BNS)
Sluice River (SLU)	Bride's Stream (BRI)	Delvin River (DEL)
Gaybrook Stream (GAY)	Jone's Stream (JON)	Mosney Stream (MOS)
Ward River (WAR)	Rush West Stream (RWS)	Nanny River (NAN)
Broadmeadow River (BRO)	Rush Town Stream (RUT)	Brookside Stream (BSS)
Lissenhall Stream (LIS)	St Catherine's Stream (CAT)	Mornington River (MOR)
Turvey River (TUR)	Rush Road Stream (RUR)	Portmarnock Estuary
Ballyboghill River (BAL)	Mill Stream (MIL)	Malahide Estuary
Corduff River (COR)	Bracken River (BRA)	Rogerstown Estuary

All watercourses in the study area flow to the Irish Sea either directly or via estuaries, as follows:

- Two watercourses, namely, the Mayne River and the Sluice River flow to the Irish Sea via Portmarnock Estuary (see Figure 4.1 in Appendix A)
- Five watercourses, namely, the Gaybrook Stream, the Ward River, the Broadmeadow River, the Lissenhall Stream and the Turvey River flow to the Irish Sea via Malahide Estuary (see Figures 4.1 to 4.4 in Appendix A)
- Six watercourses, namely, the Ballyboghill River, the Corduff River, the Baleally Stream, the Bride Stream, the Jone's Stream and the Rush West Stream flow to the Irish Sea via Rogerstown Estuary (see Figures 4.5 and 4.6 in Appendix A)
- Ten watercourses, namely, the Bracken River, the Delvin River, the Nanny River, the Rush Town Stream, the St. Catherine's Stream, the Rush Road Stream, the Mill Stream, the Balbriggan North Stream, the Mosney Stream and the Brookside Stream flow directly to the Irish Sea (See Figures 4.6 to 4.8 in Appendix A).

The Mornington River, which discharges to the Boyne Estuary, is the subject of a separate detailed flood alleviation scheme but the results from that study will be incorporated into the FEM FRAM study.

The degree of existing or potential future flood risk within the study area is more significant in some areas than others. Such areas would include existing towns and villages subject to flooding, and areas understood to be prone to flooding and for which significant development is anticipated. These areas are defined as the Areas of Potential Significant Risk (APSRs). The watercourses that are understood to give rise to the existing or potential future flood risk within the APSRs are defined as the High Priority Watercourses (HPWs). The sections of rivers and streams which are designated as HPWs are shown in red colour in Figure 1-1 and also in Figure 1 in Appendix A. In addition to the APSRs, the other areas where the flood risk is considered to be moderate are defined as the Areas of Potential Moderate Risks (APMRs). The watercourses that are understood to give rise to the existing or potential future flood risk within the APMRs are defined as the Medium Priority Watercourses (MPWs). The sections of rivers and streams which are designated as MPWs are shown in green colour in Figure 1 in Appendix A.

The extent of existing and future flooding in the rivers and streams is predicted using the hydraulic models. These hydraulic models will be constructed using the topographic survey data and LiDAR data of the HPWs and MPWs extent for all 23 rivers and streams in the study area. In order to ascertain a better distribution of design inflow in the hydraulic model to achieve accurate and representative flooding extents, the HPWs and MPWs sections of the river and streams have been further sub-divided into a total of 270 sub-catchments. Design inflows at these sub-catchments are calculated using the Flood Studies Supplementary Report 16 (NERC, 1985) and Institute of Hydrology Report No. 124 (IOH, 1994) unit hydrograph (UH) method. Detailed descriptions of the methodology used for extracting the sub-catchment characteristics and generating the design inflow are presented in Section 6. The sub-catchment nodes and their boundaries are shown in Figures 4-1 to 4-8 in Appendix A.

1.3 Objectives of FEM FRAMS

Flood risk in Ireland has historically been addressed through the use of structural or engineered solutions to existing problems, such as the implementation of flood relief schemes to protect areas already at risk of flooding. In line with internationally changing perspectives, the Irish Government adopted a new national policy in 2004 that shifted the emphasis in addressing flood risk towards:

- pro-active management of flood risk in line with the EU Floods Directive, with a view to avoiding or minimising future increases in flood risk;
- integrated flood risk management and development planning aiming at the reduction of the adverse consequences for human health, the environment, cultural heritage and economic activity associated with floods in the community; and
- increased use of non-structural and flood impact mitigation measures.

Flood Risk Assessment and Management Studies (FRAMS) and Flood Risk Management Plans (FRMP) are at the core of this national policy for flood risk management and the strategy for its implementation. These studies are being developed to meet the requirements of the EU Floods Directive on the assessment and management of flood risk, which was introduced on 26 November 2007.

The specific objectives of the Fingal East Meath FRAMS are to:

- Assess and map the spatial extent and degree of flood hazard and risk in the study area with particular focus on the Areas of Potential Significant Risk (APSR) and Areas of Potential Moderate Risk (APMR) within the study area;
- Examine future pressures such as land use and climate changes that could increase the risk of flooding;
- Build the strategic information base necessary for making informed decisions in

relation to managing flood risk (including planning and development management);

- Carry out an environmental study, known as a Strategic Environmental Assessment (SEA), to ensure that environmental issues and opportunities for enhancement are fully considered throughout the study;

- Identify viable structural and non-structural measures and options for managing the flood risks for localised high-risk areas and within the study area as a whole; and

- Develop an economically, socially and environmentally appropriate long-term strategy (a Flood Risk Management Plan (FRMP)) for the Fingal and East Meath study area. The FRMP sets out the measures and policies, including guidance on appropriate future development, that should be pursued by the local authorities, the OPW and other stakeholders to achieve the most cost effective and sustainable management of flood risk within the study area taking account of the effects of climate change and complying with the requirements of the Water Framework Directive and EU Floods Directive.

1.4 Objective and approach of hydrological analysis

The main objective of the hydrological analysis of FEM FRAMS is to estimate design flood flows within the modelled watercourses at the sub-catchment level, with a level of accuracy that ensures the development of flood inundation maps that are fit-for-purpose, and thereby, a robust and integrated FRMP.

The overall hydrological analysis will be carried out in three stages, with the following being the main objectives of each of these three stages:

- **Stage 1** - This stage focused on acquiring the hydro-meteorological data within the study area as well as in the neighbouring catchments; defining and reviewing the principal historical floods in the study area, and identifying sub-catchment locations. The findings of this phase are presented in the Inception Report published in October 2008.

- **Stage 2** – This stage consisted of statistical analyses of the hydro-meteorological data acquired in Stage 1 to define design rainfall and flows at the hydro-meteorological stations; a joint probability analysis of the coincidence of fluvial and tidal floods to determine the appropriate combinations of fluvial and tidal events; and a review and analysis of historic floods in the project area to inform the calibration/validation of the hydraulic model at later stages. The results of the analyses carried out during this phase are presented in the Preliminary Hydrology Report, published in February 2009.

- **Stage 3** – The main objective of this stage is to carry out further hydrological analysis to estimate the design flood inflow at sub-catchment level. These design inflows will be used in determining flood levels, flood extents and flood risk management options. The results of the analyses carried out during this phase are presented in this Hydrology Report.

The detailed hydrological analysis (Stage 3) includes the following activities:

i. Review of the rating at the study area gauging stations through detailed localised hydraulic modelling in ISIS 1D to derive modelled high / flood flow ratings in order to reduce any uncertainty associated with the upper range of the rating.

ii. Estimation of design floods for a range of annual exceedence probability (AEP) events at the gauging stations using the modified annual maximum series obtained from rating review at the hydrometric gauging stations.

iii. Preparation of ISIS FSSR 16 and IOH 124 input files for all sub-catchments (total 270) by extracting catchment characteristics through GIS automation and manual corrections (as necessary).

iv. Reconciliation of the flows at the hydrometric gauging stations from statistical method (step ii) and from the FSSR 16 and IOH 124 method (step iii) using the hydraulic model iterative simulation.

v. Assessment of future scenarios based on potential future land use changes in the study area and climate change.

2. Data Collection

2.1 Introduction

A significant amount of data was collected during the inception phase of the FEM FRAM study. Further data was collected during the course of study. The data which are used for the hydrological analysis can be grouped under the following headings:

- Rainfall data
- Hydrometric data
- Historic flood data
- Tidal data
- Mapping data
- Topographic survey data
- LiDAR data
- Land use data (forest cover and urban area)
- Soil data

A description of the above data is presented in the Inception Report and Preliminary Hydrology Report. A brief review of the above data is presented in the subsequent sections.

2.2 Rainfall data

Twenty-two meteorological stations were identified in the study area. Ten stations were identified which had at least nine years of recent data or which were active for some significant flood events (e.g. Hurricane Charlie - August 1986). These stations are Stations 532, 632, 1032, 1332, 1532, 1632, 2232, 2332, 2432 and 2532. In addition, four stations in the neighbouring catchments, namely, Stations 3723 (Casement Aerodrome), 931 (Kells, Headfort), 2931 (Warrenstown) and 2638 (Ardee) were also considered to have sufficient data for this analysis. Rainfall data for these fourteen stations was provided by Met Éireann.

The locations of the meteorological stations are shown in Figure 2 in Appendix A. Table B-1 in Appendix B presents a summary of these meteorological stations. Detailed analysis of rainfall data is presented in Section 5 of Preliminary Hydrology Report and a summary of that study is presented in Section 4 of this report.

In addition, the Flood Study Update (FSU) depth duration frequency (DDF) model, FSU standard period annual average rainfall (SAAR), Jenkinson's ratio (r) in the study area were provided by the OPW in a GIS layer.

2.3 Hydrometric data

The Project Brief identified a total of ten hydrometric stations in the study area (Hydrometric Area (HA) 08). These stations are listed in Table 2-1.

Table 2-1: Hydrometric stations listed in the Brief

Station Number	Station Name	River / Stream	Data Provider
08002	Naul	Delvin	EPA
08003	Fieldstown	Broadmeadow	EPA
08005	Kinsaley Hall	Sluice	EPA
08007	Ashboune	Broadmeadow	EPA
08008	Broadmeadow	Broadmeadow	OPW
08009	Balheary	Ward	EPA
08010	Garristown	Garristown	EPA
08011	Duleek	Nanny	OPW
08012	Ballyboghill	Ballyboghill	EPA
08017	Duleek (u/s)	Nanny	OPW

Of the ten hydrometric stations in the study area, seven stations were installed by the Local Authorities (Dublin County Council and Meath County Council) with the data processed by An Foras Forbartha (AFF) or the Environmental Protection Agency (EPA), as relevant. The hydrometric data for these stations was provided by the EPA (hereafter called the EPA stations). The remaining three stations were installed by the OPW (hereafter called the OPW stations). All the EPA stations are obsolete now, as these were closed between 1995 and 2001. The available hydrometric data at these hydrometric stations was provided by the EPA.

Two of the OPW stations (namely, Station 08008 and 08011) are still in operation and for which hydrometric data was made available by the OPW. No hydrometric data was available for the third OPW station, namely, Station 08017 Duleek (u/s). This station is located upstream of the Drogheda Road Bridge whereas Station 08011 Duleek is located downstream of the same Drogheda Road Bridge on the Nanny River at Duleek. As no tributary of the Nanny River joins between stations 08011 and 08017, exclusion of hydrometric data of Station 08017 Duleek (u/s) is considered not to affect the overall results of the hydrological analysis.

A short series of instantaneous flow and water level records from early September 2008 to mid-November 2008 were available for a gauging station on the Cuckoo Stream (a tributary of the Mayne River) installed by the Dublin Airport Authority. As the data was less than one year, the data was not considered for the hydrological analysis.

To augment the relatively low level of data available in the study area (HA 08) for statistical analysis using pooling group method, the hydrometric data from the neighbouring gauging stations (namely, from HA 07 and HA 09) was collected from the OPW and the EPA. The OPW data for the neighbouring catchments include instantaneous flows, water levels and the annual maximum series (AMS) data for nine stations namely, Station 07002 Killyon on the Deel River, Station 07003 Castlerickard on the Blackwater River, Station 07005 Trim on the Boyne River, Station 07006 Fyanstown on the Moynalty River, Station 07007 Boyne Aqueduct on the Boyne River, Station 07009 Navan Weir on the Boyne River, Station 07010 Liscartan on the Blackwater River, Station 07012 Slane Castle on the Boyne River and Station 09001 Leixlip on the Ryewater River. Similarly, the EPA provided hydrometric data for the neighbouring catchment include instantaneous flows and water levels for three stations, namely, Station 09002 Lucan on the Griffeen River (operated by South Dublin County Council), Station 09037 Botanic Gardens on the Tolka River and Station 09102 Cadbury's on the Santry River (both operated by Dublin City Council).

The description of the above hydrometric data is presented in Section 2 and Appendix C of the Preliminary Hydrology Report.

The EPA provided hydrometric data for three other hydrometric stations in the study area, namely, Station 08004 Owen's Bridge on the Ward River, Station 08006 Hole in the Wall on the Mayne River and Station 08014 Skerries on the Mill Stream. The quality and completeness of the data was assessed and the findings are presented in the following paragraphs.

Station 08004 Owen's Bridge on the Ward River consists of hydrometric data from 27/10/1976 – 11/03/1981 (less than 5 years). The rating is limited to low and medium flows only and the high flows are extrapolated from this rating curve. According to the 'FCC Report on Fingal Hydrometric Stations' (dated 6th August 2008), the old station was on a lake, which is now a reservoir. The FCC report proposed to relocate this station at Coolrath Bridge. The station was not included in the OPW review of gauging stations (Hydro-Logic, 2006), and hence the rating quality of this station is not known. As the area is already developed (EPA comments dated 31 August 2009), a rating review with the current river section would not represent the old gauging station. Therefore no further analysis of the hydrometric data and no detailed rating review were carried out.

Station 08014 Skerries on the Mill Stream consists of hydrometric data from 13/05/1983 to 22/08/2001. The data consists of several gaps in the years 1983, 1984, 1994, 1995, 1996, 1997, 1998, 1999, 2000 and 2001. The datum of this station is not referenced to the Malin Head or Poolbeg Ordinance Datum but to a temporary bench mark. The EPA rating at this station is based on low and medium flow regimes and hence the high flows are extrapolated from this rating curve. The station was also not included in the OPW review of gauging stations (Hydro-Logic, 2006), and hence the high flow quality of this station was not known. According to the 'FCC Report on Fingal Hydrometric Station', access to the old station is difficult and hence this station is to be relocated beside the Railway Bridge. Due to the above reasons, no further analysis of the hydrometric data and no detailed rating review were carried out.

Station 08006 Hole in the Wall on the Mayne River consists of approximately 10 years of hydrometric data, i.e., from 09/03/1977 to 01/03/1987. The data consists of several gaps in the years 1977, 1985, 1986 and 1987. The zero datum at the gauge changed four times in 1977, three times in 1978 and one time in 1981 whereas the rating equation changed seven times in the ten years. The station was also not included in the OPW review of gauging stations (Hydro-Logic, 2006) and hence the high flow rating quality of this station was unknown. Therefore the data was not further analysed and not included in the hydrological analysis. However, this station is considered to provide valuable information for the calibration of the hydraulic model of the Mayne River in the future. According to the 'FCC Report on Fingal Hydrometric Stations', the old station at the Hole in the Wall Road is to be renewed subject to funding being made available. It is therefore recommended the reinstallation of the Station 08006 Hole in the Wall Road on a priority basis so that the existing (with rating review) and future hydrometric data at this station could provide useful information for the forecasting of flood flows in the Mayne River.

The locations of all the above hydrometric stations are shown in Figure 3 in Appendix A. A summary of the hydrometric stations and the available data is presented in Table B-2-1 in Appendix B.

2.4 Historic flood data

A record of at least 141 historic flood events in the study area since the 1940's was made available by the OPW in GIS layer. The relevant reports on these historical flooding events have been downloaded directly from the OPW National Flood Hazard Mapping website www.floodmaps.ie. Historic flood reports, including those on the recent flooding in summer 2008, were also received from FCC, MCC and from a number of organisations and websites. Information on the August/September 2008 flooding in the study area was also collected by Halcrow Barry during the defence asset field survey. A list of flooding events in the study area is presented in Tables B-3-1 to B-3-3 in Appendix B.

2.5 Tidal data

The Department of Agriculture, Fisheries and Food (DAFF) provided predictive coastal flood outlines produced by the Irish Coastal Protection Strategy Study (ICPSS). According to the "*Irish Coastal Protection Strategy Study, Phase III – Extreme Flood Outline, Floodplain Mapping and Erosion Risk Assessment – Draft Final Technical Report*" prepared for the DAFF in August 2008, the study used numerical modelling of combined storm surges and tide levels to obtain extreme water levels along the coastline between Dalkey Island and Omeath. According to the above report, a Digital Terrain Model (DTM) developed by the DAFF was used in the study to define the extent of the predictive floodplain. The predictive flood outlines were calculated by combining the results of the surge and tide level modelling, the statistical analysis, and the DTM using GIS technology.

The DAFF provided water levels and flood outlines for design events with exceedence probabilities of 50%, 20%, 10%, 5%, 2%, 1%, 0.5% and 0.1%. The OPW provided historic tide data at Dublin Port and at Port Oriel, Clogherhead.

Using the DAFF design event water levels and the Admiralty Tide Tables Volume 1, 2007: United Kingdom and Ireland, (*United Kingdom Hydrographic Office, ISBN 0-70-771-5954*), design event tide series were generated for range of AEPs, namely, 50%, 20%, 10%, 4%, 2%, 1%, 0.5% and 0.1%, at 13 locations at the mouths of rivers and estuaries in the study area (See Figure 2-1).

It is noted that the DAFF provided data did not include water levels at the design event of 4% AEP. For this purpose, the predicted water surface levels were plotted on a semi-log plot against the range of AEP for which tidal data was available from the DAFF. The resulting plots were used to derive design water levels for the 4% AEP event.

Figure 2-1: Mouths of rivers and estuaries for the generation of predicted tidal series

2.6 Mapping data

The following mapping data for the FEM FRAM study area has been received by Halcrow Barry (under licence to the OSi) from FCC and MCC:

- Discovery series 50,000 scale raster maps
- 2,500 scale raster maps
- 2,500 scale vector maps
- Aerial photography of the study area

2.7 Topographic survey data

The topographic survey of the channel cross sections, structure details and geometry of the defence assets in the FEM FRAM study area has been carried out under a separate contract. The topographic data was used for developing localised detailed hydraulic modelling for rating review.

2.8 LiDAR data

The following LiDAR data of the study area was provided by the OPW:

- the 2m, 5m and 10m DTM (digital terrain model) covering the HPWs, MPWs, APSRs and APMRs

- the 2m DEM (digital elevation model) covering the HPWs, MPWs, APSRs and APMRs
- the 2m low tide LiDAR DTM at the coastal area and estuaries

In addition to the above, the hydrologically corrected DTM (hDTM) of 20m resolution was available from the EPA.

The 2m LiDAR DTM was used to extend the surveyed channel cross sections on the floodplain. The hydroDTM was used for delineating sub-catchment boundaries and for extracting catchment characteristics of the sub-catchments

2.9 Land use and soil data

The land use data collected was the Corine land cover data (2000) and its update (2004). The county development plans of the study area were provided by FCC and MCC. The soil and subsoil data was available from the EPA. The land use data and the soil data was used for extracting the catchment characteristics of sub-catchments and for assessing the future environmental and land use changes in the study area.

3. Review and analysis of historic floods

3.1 Collection of historic flood data

Information on historic flooding in the study area was collected from various sources. The main source of information of historic flood is the OPW National Flood Hazard Mapping website www.floodmaps.ie which provides an abundance of historic flood information throughout Ireland. A record of at least 141 historic flood events in the study area since the 1940's was made available by the OPW in GIS (MapInfo) layer. The relevant reports on these historical flooding events were downloaded directly from the website www.floodmaps.ie.

Historic flood reports, including those on the recent flooding in summer 2008, were also received from FCC, MCC and from a number of organisations, websites and individuals. Information on the August/September 2008 flooding in the study area was also collected by Halcrow Barry during the defence asset field survey.

3.2 Flooding mechanism in the study area

The study area differs from other catchments in Ireland as despite a low annual rainfall, small catchment areas and catchment slope, it is highly susceptible to extreme flood events, as particularly demonstrated in recent years. The review of historic flooding presented here is related to the surface water flooding; the groundwater analysis is being carried out separately under FEM FRAM study.

The surface water flooding in the study area are classified into four categories, namely, fluvial flooding, pluvial flooding, tidal flooding and combination of fluvial and tidal flooding. A brief description of these four types of flooding is presented below.

Fluvial flooding occurs when rivers overflow and burst their banks, due to high or intense rainfall resulting high surface runoff flowing into them. Fluvial flooding is most commonly caused by intense bursts of rain causing flash floods or prolonged rainfall on saturated ground in the river catchment, which increase flows in the rivers and watercourses, exceeding their in-bank flow capacity and overflowing their banks.

Pluvial flooding is defined as flooding from rainfall-generated overland flow, before the runoff enters any watercourse or sewer. It is associated with high-intensity or prolonged periods of rainfall and is characterised by overland flow and ponding in depressions in the topography. Pluvial flooding occurs when rainfall cannot be absorbed by the ground or drainage system.

Tidal and coastal flooding can occur during exceptionally high tides or during storm events when low pressure systems result in storm surges that batter the coast lines and funnel water up the estuaries. Wind action causes increased wave heights which also contribute to coastal flooding.

Combined fluvial and tidal flooding event is the one when both the fluvial and tidal flooding events occur at the same time.

The historic flood data collected from various sources were reviewed and reported in Section 4 of Preliminary Hydrology Report. List of the flooding events in the study area is presented in Tables B-3-1 to B-3-3 in Appendix B. Table B-3-1 also presents a brief description of the fluvial flooding in the study area. The pluvial flooding and coastal/tidal flooding are being analysed separately under FEM FRAM study.

The most 'significant' flooding events in the study area are listed in Table 3-1.

Table 3-1 – Significant recent fluvial and tidal flood events within the study area

Flood Event Date	Main Flood Mechanism	Rivers/Coast Affected	Areas Affected:
1924*	Tidal	Coastal	Coastal area of Fingal and Meath counties
December 1954	Fluvial	Nanny River	Washed away Drogheda Bridge
November 1982	Fluvial	Ward River, Broadmeadow River, Mill Stream	Swords, Malahide, Skerries
August 1986	Fluvial	Broadmeadow River, Ward River, Mill Stream, Nanny River	Swords, Skerries, Balbriggan, Duleek
June and October 1993	Fluvial	Mayne River, Nanny River	Balgriffen, Duleek
February 2002	Tidal	Ward River, Mayne River, Turvey River, Sluice River	Swords, Portmarnock, Maynetown, Skerries, Portrane, Bettystown, Malahide, Rush
October/November 2002	Fluvial	Ward River, Sluice River, Mill Stream, Ballyboghill River	Portmarnock, Swords, Malahide, Skerries, Ballyboghill, Donabate, Portrane, Rush, Balbriggan
November 2000/ November 2004	Fluvial/tidal	Sluice River, Brooks Stream, Mayne River	Bettystown, Rush, Skerries
August 2008	Pluvial/fluvial	Sluice River, Hazelbrook Stream, Gaybrook Stream near Swords, Corduff Stream	Lusk, Ashbourne, Malahide, Swords, Kinsaley Village

**The Dublin Coastal Flooding Protection Project Final Report (2005) has reported this extreme tidal even in 1924 whereas the Mornington District Surface Water & Flood Protection Scheme Final Preliminary Report (2004) has reported this anecdotal event in 1922.*

It is observed from Table 3-1 that, the major flood events in the last 23 years were the August 1986 (Hurricane Charlie), the November 2000 and the November 2002 (see Figure 3-1), which all resulted in considerable flood damage in the study area. The highest recorded tidal levels in Dublin Bay occurred in February 2002, resulting in tidal damage to properties along the Fingal and Meath coast. More recently, surface water flooding has occurred during the summer of 2008, which caused damage to property and disruption to the road network.

Figure 3-1: Flooding at North Street, Swords, November 2002 (Photo: FCC)

3.3 Summary of flooding mechanism

From a review of historical flood events in the study area, it has been observed that the study area is generally affected by four types of flooding; namely:

- Fluvial flooding due to intense rainfall in the study area rivers/streams catchment which results in severe flooding in the rivers and streams. For example, the December 1954 flooding in the Nanny River, the November 1982 flooding in the Ward and the Broadmeadow Rivers and the August 1986 flooding (Hurricane Charlie) in the Ward, Broadmeadow and Nanny Rivers were the major fluvial flooding in the study area.
- Pluvial flooding during intense rainfall periods as a result of restricted pipe sizes, under-capacity bridges and culverts and debris causing blockages. For example, the August 2008 flooding at Lusk, Ashbourne, Malahide, Swords, Kinsaley village etc.
- Tidal/coastal flooding due to exceptionally high sea water levels. For example, the February 2002 coastal flooding at Portmarnock, Malahide, Portrane, Swords, Skerries, Rush and Bettystown; and the 1924 tidal flooding (anecdotal) at the Fingal and Meath coastal areas were the major tidal/coastal flooding in the study area.
- Combined fluvial and tidal/coastal flooding due to fluvial flooding (resulting from intense rainfall at the study area rivers/streams catchment) and tidal flooding occurring at the same time. For example, the November 2000 and November 2004 flooding at Skerries, Rush, Bettystown areas.

4. Meteorological Analysis

4.1 Introduction

A detailed rainfall analysis of the stations within the study area and some stations from the neighbouring catchments was carried out during the preliminary hydrology analysis and, therefore, no further rainfall analysis was carried out during the present phase. The results of the rainfall analysis are presented in Section 5 and Appendix B of the Preliminary Hydrology Report. A summary of the result is presented in the subsequent paragraphs.

The primary outputs produced from the analysis of the meteorological data were:

- Estimation of one hour duration rainfall of various return periods at Dublin Airport;
- Estimation of two day duration rainfall of various return periods at the gauging stations within the study area and also the 2-day rainfall growth curve for the study catchment;
- Estimation of probabilities for the major and recent events in the study area with respect to the above results.

The analysis of rainfall data was undertaken following the approach of the Flood Studies Report (FSR) Volume 2 - Meteorological Studies (*Section 2: Regional analysis of point rainfall extremes* and *Section 3: Estimation and mapping of M5 value for different duration*) and the UK Flood Estimation Handbook Volume 2 - Rainfall frequency estimate (*Chapter 8 – Deriving growth curves*). The results of this analysis were compared with Depth-Duration-Frequency curves of the Flood Studies Update – Rainfall Analysis.

4.2 Analysis of rainfall data

4.2.1. Data used

The rainfall data for 14 stations (10 from the study area and 4 from neighbouring catchments) was provided by Met Eireann. This included hourly rainfall data at Dublin Airport and daily rainfall data for the other stations. From the quality checking of the rainfall data, two stations were found to have several long gaps, thus having less than nine years of complete data. According to FEH, the required minimum continuous record length is nine years to ensure that the median value of annual maximum 2-day rainfall series (Rmed) is reasonably estimated. With this, 12 rainfall data sets were finally selected for further analysis (refer to Table 4.1 below). Details of the meteorological data are presented in Table B-1 in Appendix B.

4.2.2. Annual maximum hourly rainfall series

A quartile analysis was carried out involving the annual maximum hourly rainfall series at Dublin Airport following the procedure of FSR Volume II Section 2.2. From the quartile analysis, the value of 1-hour fixed duration rainfall of five year return period (M5-1hr) was estimated as 13.3mm. Applying a factor of 1.15 to convert the fixed duration rainfall to sliding duration rainfall as recommended in the Technical Note 61 (Fitzgerald, 2007), the value of 1-hour rolling duration rainfall of 5-year return period (M5-60) at Dublin Airport would be approximately 15.3 mm. This value is close to the FSU Depth Duration Frequency model M5-60 value at Dublin Airport, which is approximately 15.7mm.

Similarly, the median value of 1-hour fixed duration rainfall (which is equivalent to 2-year return period) at Dublin Airport was estimated as 9.6mm. Applying a conversion factor of 1.15 as above, the 1-hour rolling duration rainfall of two year return period would be 11.04mm. This value is close to the FSU-DDF model 1-hour rainfall of two year return period at Dublin Airport, which is approximately 11.2 mm.

4.2.3. Annual maximum two day rainfall series

The analysis of the annual maximum 2-day rainfall series of all the twelve gauging stations was carried out in a similar way to the above analysis. The annual maximum 2-day rainfall series were then plotted against the Gumbel reduced variate for all twelve stations individually. Standardised values of 2-day fixed duration rainfall (AMfixed-2day / RMedFixed – 2day) were pooled together as described in Section 8, Volume 2 of FEH. The plot of standardised 2-day rainfall against Gumbel reduced variate (reproduced on Figure 4-1) shows that the average value of 100-year growth factor in the FEM FRAM study area is approximately 2.10.

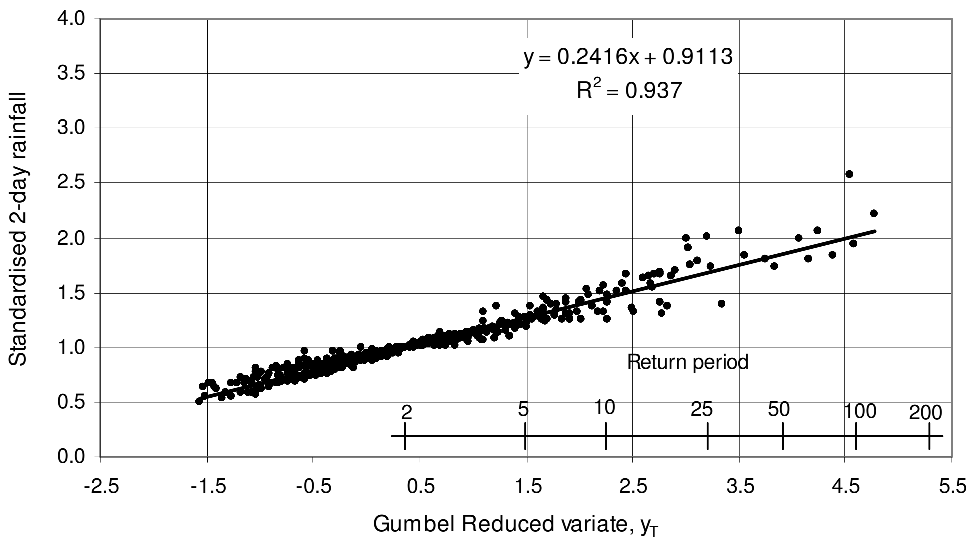

Figure 4-1: Plotted points of annual maximum 2-day rainfall (mm) for the study area

It is suggested in FEH that the pooled points alone cannot define the growth curve of higher return periods. Therefore, using the techniques of FSR Volume II Section 2.2, quartile analyses were carried out involving all twelve rainfall series, for the estimation of higher return period extreme rainfall values. Figure 4-2 shows that a parabolic line can define the relationship of 2-day rainfall against the Gumbel reduced variate.

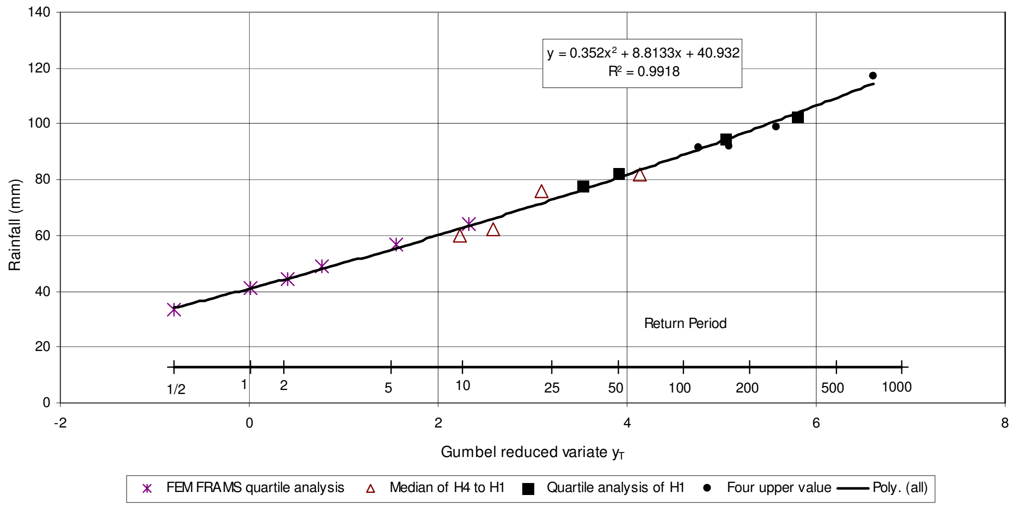

Figure 4-2: Study area frequency curve (2-day duration rainfall) from the quartile analysis

It is observed from Figure 4-2 that the 2-day fixed duration rainfall values of 2, 5, 10, 25, 50, 100, 200, 500, and 1000 year return periods for FEM FRAMS are approximately 44.2, 54.9, 62.6, 72.7, 80.7, 88.9, 97.5, 109.3 and 118.6mm respectively. Using a factor of 1.08 (refer: TN 61 by Fitzgerald, 2007), to convert the fixed duration to rolling duration rainfall, the corresponding rainfall values for the above return periods are 47.7, 59.3, 67.2, 78.5, 87.2, 96.0, 105.3, 118.0 and 128.1mm respectively.

The Depth Duration Frequency (DDF) mapping of Ireland has been carried out jointly by the OPW and Met Éireann as part of the ongoing Flood Studies Update. OPW provided the results of the FSU-DDF mapping, in the form of point rainfall values at each 2km x 2km grid, for the duration of 0.25 hr to 600 hrs and for the 2, 5, 10, 20, 30, 50, 100 and 200 year return periods. The 2, 5, and 100-year return period 2-day rolling duration rainfall (obtained by applying a conversion factor of 1.08 as above) estimated by the present study is compared with the corresponding values of FSU-DDF curve. Summary of the station-based comparison of the 2-day rolling duration (48-hours) rainfall of 2 and 5-year return periods are presented in Table 4-1. The last two rows of Table 4-1 compare the values of 2, 5 and 100-year return period rainfall obtained from the quartile (regional) analysis of the 12 station with those of the median values of the FSU-DDF curve for the corresponding return periods.

Table 4-1: FEM FRAMS results compared with those of FSU - DDF curve

Station Name	Station ID	Data availability (N years)	FEM FRAMS 48-hr rainfall of return periods		FSU-DDF curve 48-hr rainfall of return periods		
			2yr	5yr	2yr	5yr	100yr
Dublin Airport	532	1941-'07 (67)	48.4	60.9	44.3	57.0	102.0
Lusk	632	1949-'85 (36)	47.9	59.5	44.0	55.5	94.0
Duleek	1032	1979-'91 (33)	47.5	56.7	45.5	58.3	104.5
Malahide	1332	1965-'06 (26)	52.5	61.7	44.0	55.8	98.8
Bellewstown	1632	1975-'83 (9)	58.5	68.7	42.8	53.3	89.5
Bellewstown (Collierstown)	2332	1997-'06 (10)	52.4	66.4	43.3	54.5	93.5
Ratoath	2432	1998-'06 (9)	49.7	65.5	44.3	55.5	92.7
Dunshaughlin	2532	1998-'06 (9)	49.4	63.8	44.5	56.3	96.5
Casement	3723	1954-'06 (53)	49.1	62.6	48.2	63.2	137.0
Kells	931	1941-'06 (45)	43.1	51.4	42.7	52.5	84.5
Warrenstown	2931	1952-'06 (55)	46.7	58.6	44.4	58.0	107.5
Ardee	2638	1968-'06 (39)	44.0	56.3	47.5	59.5	93.5
FSU – DDF (12 stations median value)					**44.3**	**56.1**	**95.3**
FEM FRAMS 48-hr rainfall from quartile analysis					**47.7**	**59.3**	**96.0**

Table 4-1 shows that the 2, 5 and 100-year return period 48-hour rolling duration rainfall values obtained from the regional analysis of 12 stations are close to the median values of the 12 stations obtained from the FSU-DDF curve for the corresponding return periods. However, a station-base comparison of the 2 and 5-year return period 48-hour rolling duration rainfall shows variation of the results from the FSU-DDF curve, especially for the stations having shorter (and most recent) data sets. For example, at Station 2332, which has 10-years of data, the 2 and 5-year return period 48-hour rolling duration rainfall from the present study are 52.4 and 66.4 mm respectively, and only 43.3 and 54.5 mm respectively from the FSU-DDF curve.

This variation in results could be for the following reasons:

- According to Technical Note 61 (Fitzgerald, 2007) the FSU analysis considered only those rainfall stations which has longer than 20 years of rainfall records, whereas the present study has considered rainfall records of longer than 9 years. The marked variations were generally observed at the stations having shorter data length.
- For the FSU-DDF curve, the rainfall data was considered up to the year 2004, whereas the present study has considered data up to 2007 for one station and up to 2006 for a further 8 stations (See Table 4-1)
- According to Technical Note 61, for most stations, the estimations were made by using up to 6 neighbouring stations with similar annual average rainfall, whereas in Table 4-1, the individual station values are based on only one station.
- The observed difference between the results of the present analysis and those of FSU-DDF rainfall values at some stations are therefore understandable. However, on

a regional (project area) basis, these differences are not significant, as observed in the last two rows of Table 4-1.

4.2.4. Summary of meteorological analysis

The study analysed twelve rainfall series with data records of 9 to 67 years. Out of these, eight stations are within the FEM FRAM study area and four stations are from the neighbouring catchments. The data was analysed both individually and in a group following the procedures of both the FSR Volume II – Meteorological Analysis and the FEH-Rainfall Analysis. The results of the study were compared with those of the Depth Duration Frequency curves of the FSU.

The study area 2-day rolling duration rainfall values of various return periods from the present analysis are somewhat similar to the median of the 12 station values from the FSU-DDF curve. However, the individual stations 2-day rolling duration rainfall are generally higher than the corresponding FSU-DDF curve value, especially at the stations having shorter and most recent rainfall data. These differences could have arisen due to the fact that the FSU-DDF study involved longer than 20 years rainfall records and also these records were up to the year 2004. The present study involved longer than nine year rainfall records and also these records were up to the year 2007.

It is noted above that the results of the group analysis (involving all 12 rainfall datasets) were close to the corresponding values of FSU-DDF curve. The FSU-DDF curves were derived from a comprehensive study using records longer than 20 years until 2004 throughout Ireland. Based on the greater regional and temporal scope of datasets used, the FSU-DDF curves will be broadly adopted for estimating the design floods in the watercourses of the study area. However, the results of the individual rainfall data analysis suggest that the FSU-DDF curve underestimates the rainfall values at stations with rainfall records less than 20 years, particularly at Bellewstown, at Ratoath and at Dunshaughlin. Therefore, the FSU-DDF curve values will be scaled, in accordance with the results of the present study, at the sub-catchments in the vicinity of these stations.

In general, the FSU-DFF model obtained values are applied to all sub-catchments, as mentioned above. The FSU-DDF model values are only scaled up for some sub-catchments in the vicinity of the three rainfall stations (Bellewstown, Ratoath and Dunshaughlin) where the rainfall values were found to be higher than the FSU DDF model. If this scaling is not applied, the design flood values estimated using FSSR 16 UH method at the ungauged catchments could be underestimated. However, for gauged catchments the FSSR 16/IOH124 UH method derived inflows will be reconciled at the hydrometric stations with the statistical method obtained design floods. The scaling of rainfall values locally at the gauged sub-catchments is therefore not considered to be a manipulation of the values based on different record lengths.

5. Hydrological Analysis

5.1 Introduction

This chapter reports on the hydrological analysis carried out to estimate the design floods for a range of AEP events at the hydrometric stations in the FEM FRAM study area. The analysis is focused on maximising the potential accuracy of design flow estimates that will, in-turn, be used for subsequent hydraulic modelling, flood mapping and flood management options development. The methodology is summarised as follows:

- A rating review was undertaken to improve the 'low confidence' associated with the gauging stations and high flow data was re-generated from the hydrometric level record;
- The index flood of individual hydrometric gauges was calculated from the re-generated flow record. In this study the Median Annual Flood (Q_{med}) is used as the index flood, consistent with the Flood Estimation Handbook and the upcoming FSU;
- The relationship between the index flood, Q_{med} and other more extreme floods is defined by the growth curve. This study has used the Flood Estimation Handbook statistical techniques to derive a study growth curve from flow records;
- Determination of confidence interval of the design floods;
- Selection of calibration events for the hydraulic models.

5.2 Rating curve review

Rating curves provide a relationship between stage and discharge (i.e., river water level and flows in a river), which can be defined at any location along a river reach. Hydrometric gauging stations generally record the water levels at a particular location along a river reach and the rating curve is used to produce a flow estimate from these recorded water levels.

The rating curve is established through recorded field measurements of flow against a recorded water level for a range of water levels, known as spot gaugings. Extrapolation of the rating curve is often necessary as spot gaugings generally do not cover the full range of water levels at a gauging station. For example, during high river flows spot gaugings are difficult to record due to flood conditions and the fact that gauging structures are often drowned. As part of the inception process, the high flow ratings for each gauge in the catchment were assessed based on information received from the EPA and OPW and the Hydro-Logic report "Review of Flood Flow Ratings for Flood Studies Update" (March 2006).

A detailed rating review was undertaken for nine out of the ten hydrometric stations listed in the Clients Brief. No rating review was carried out for the 10^{th} station (08017 – Duleek u/s on the Nanny River) as the station is located just upstream of Station 08011-Duleek on the Nanny River, and no hydrometric data was available from the OPW for this station. Table 5-1 provides details of the hydrometric gauging stations including station number, location and type of gauge. Figure 3 in Appendix A shows the location of these gauging stations.

Table 5-1 Details of the hydrometric gauging stations used in the rating review

Gauging station	Location	River/Stream	Managing organisation	Gauge type
08002	Naul	Delvin	FCC/EPA	Weir / open channel
08003	Fieldstown	Broadmeadow	FCC/EPA	Open channel
08005	Kinsaley Hall	Sluice	FCC/EPA	Weir / open channel
08007	Ashbourne	Broadmeadow	MCC /EPA	Open channel
08008	Broadmeadow	Broadmeadow	OPW	Weir
08009	Balheary	Ward	FCC/EPA	Weir
08010	Garristown	Garristown	FCC/EPA	Weir/ Open channel
08011	Duleek	Nanny	OPW	Open channel
08012	Ballyboghill	Ballyboghill	FCC/EPA	Weir / open channel

The activities undertaken for the rating review at each station include:

A. Visiting the hydrometric station site;

B. Obtaining river survey cross sections (in-bank) in the vicinity of the hydrometric station and extending these survey sections to the floodplain using the LiDAR based DTM. The river section survey data was obtained through a separate contract (DigiTech 3D) and the LiDAR data was obtained from the OPW. Some discontinuities were found when extending the topographic survey into the floodplain. In such cases, the DTM was adjusted to match the topographic survey. Details of any significant discontinuities encountered during the hydraulic modelling task will be reported in the hydraulic report;

C. Modelling of a short stretch of river in the vicinity of the station in the ISIS 1D model using the above extended river cross sections;

D. Simulating the ISIS model in unsteady flow condition for various values of weir/bridge coefficients and Manning's roughness factors (n) so as to obtain a range of stage-discharge relationships at the gauging station;

E. Plotting the spot flow measurements and historical rating curves acquired from the EPA/OPW together with the stage-discharge relationships (obtained in step D) on normal and double log plot for comparison purposes;

F. from the visual comparison of the plots in Step E, obtaining the most appropriate sections of the proposed rating curve.

The rating curve review assessed the existing rating and extended the rating curve to high flow using local hydraulic computer models and followed guidance in the "Extension of Rating Curves at Gauging Stations – Best Practice Guidance Manual, R & D Manual W06-061/M (2003)" produced by the UK Environment Agency. As the main purpose of the rating review was to define the upper range of the stage-discharge relationship, the low flow ratings were adopted from those obtained from the EPA and the OPW. For the medium flow regime, the ISIS based rating and the EPA and the OPW rating match in most cases. However, for the high flow stages, the ISIS based stage-discharge relationship is adopted to extend the rating curves.

The hydrometric data (instantaneous series and annual maximum series), the number of rating curve available from the EPA/OPW and the datum used (Poolbeg / Malin Head) at the nine stations are presented in Table 5-2.

Table 5-2: Details of hydrometric data, number of rating curve and the datum used

Hydrometric Station	Hydrometric data available		Datum (m OD)		Number of rating curve
	Instantaneous	AMS	Poolbeg	Malin Head	
08002 Naul	1977 - 2001		61.618	58.905	2
08003 Fieldstown	1976 - 1998		33.039	30.326	14
08005 Kinsaley Hall	1977 - 2001		6.473	3.760	4
08007 Ashbourne	1977 - 1997		64.08	61.367	3
08008 Broadmeadow	2006 - 2008	1978 – 2006	8.65	5.937	1
08009 Balheary	1980 - 1996		5.953	3.240	2
08010 Garristown	1983 - 1997			93.716	1
08011 Duleek	1979 - 2008	1979 - 2008	19.15	16.437	6
08012 Ballyboghill	1980 - 1999		29.807	27.094	5

It is observed from Table 5-2 that two stations, namely, Station 08008 Broadmeadow and Station 08010 Garristown have only one rating equation, whereas the other stations have more than one rating equation. For stations having more than one rating equation, the most recent rating was adopted for extending it in the high flow regime. This is because the surveyed channel cross sections are considered to represent the most recent hydraulic properties of the channel at the vicinity of the gauging station. Similarly, for the stations having more than one datum, the most recent datum was adopted for extending the rating curve in the high flow regime (see Table 5-2).

For the station having only one rating curve (e.g., Station 08008 and 08010), the proposed reviewed rating curve can be used directly. However for the station having more than one rating, the proposed reviewed rating can be used directly only for the period for which the most recent rating was suggested by the EPA/OPW. For the previous rating periods, the EPA/OPW suggested rating curves (for the corresponding periods) can be used for the low and medium flow regime and the extended rating can be used for the high flow regime, with the adjustment of gauge height if the datum was also different from the current datum of Table 5-2 (refer to Section 5.3.2 for detail).

Figure 5-1 and Table 5-3 show the revised rating for Station 08012 Ballyboghill on the Ballyboghill River. Further information on the rating curve of other gauging stations is available in Appendix C1.

Table 5-3: Parameters of the revised rating equation $Q(h) = C*(h+a)^b$ for Station 08012 Ballyboghill on the Ballyboghill River

Section	Minimum stage (m)	Maximum stage (m)	C	A	b	Adopted rating
1	0.200	0.308	3956.68	-0.20	5.40	EPA
2	0.308	0.544	19.28	-0.20	3.01	EPA
3	0.544	1.000	3.700	-0.20	1.60	HB
4	1.000	1.500	4.200	-0.20	2.10	HB
5	1.500	1.700	3.450	-0.20	2.80	HB
6	1.700	2.000	2.450	-0.20	3.60	HB

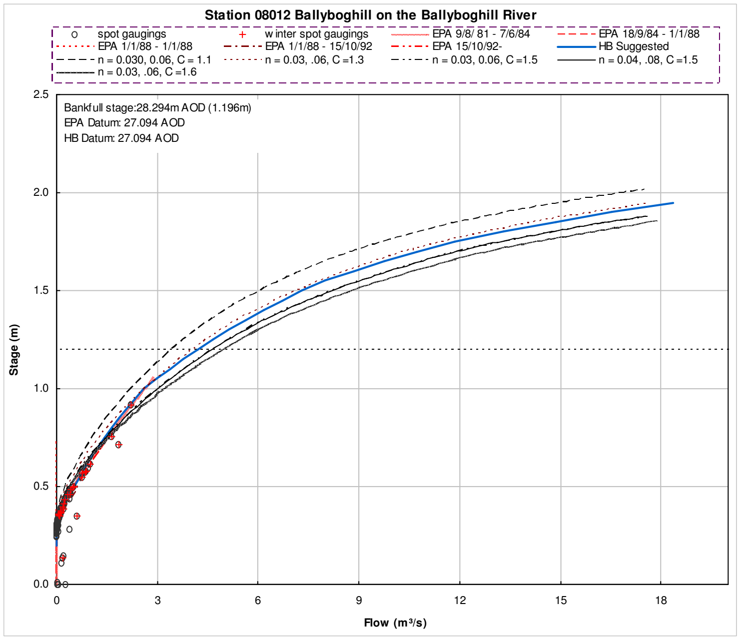

Figure 5-1: Proposed rating curve for Station 08012 Ballyboghill on the Ballyboghill River

A Technical Note on the outcome of rating review was issued to the OPW on 24 August 2009 with a request for forwarding it to the EPA. The Technical Note identifies some issues at some hydrometric stations. A response received on the rating curve review for the OPW Stations 08008 Broadmeadow and Station 08011 Duleek has been incorporated and discussed in Appendix C. Preliminary response received from the EPA has also been incorporated.

5.3 Index flood

5.3.1. Median annual maximum flood Q_{med}

The average annual maximum flood (Q_{bar}) has typically been used as the index flood in Ireland, in accordance with the Flood Studies Report (NERC, 1975). However, hydrological practitioners now have a strong preference for using the Median Annual Flood (Q_{med}) instead of Q_{bar}, as the estimate is not susceptible to the inclusion or omission of isolated extreme events. The Q_{med} estimate is potentially more accurate from shorter data records than Q_{bar}. The UK FEH adopts Q_{med} as the standard index flood. It is understood that the ongoing Irish Flood Study Update (FSU) is also recommending the use of Q_{med} instead of Q_{bar} as the index flood for Ireland. Therefore, Q_{med} is considered the appropriate index flood for the FEM FRAMS hydrological analysis.

The median flow Q_{med} is defined as the flood that is expected to occur or be exceeded, on average, every other year. In statistical terms, the Q_{med} flood is said to occur or be exceeded on average once every two years and have a 50% probability of annual exceedence.

5.3.2. Annual maximum series and Q_{med} at gauged catchments

The FEM FRAM study area hydrometric stations consist of annual maximum series whose record length range from 13 years (Station 08010 Garristown) to 28 years (Station

08011Duleek on the Nanny River). The FEH (Volume 3, Section 2.2) recommends that annual maximum records greater than 14 years be used for Q_{med} estimation, below which peak over threshold records should be used. One station used in this study has a shorter data record than that recommended (13 years), but is considered to not affect the generality of the result and hence for all stations the annual maximum series was considered.

The treatment of water levels in the rating review methodology is summarised as:

- ISIS river models were developed in the vicinity of the gauging stations. The models produce water levels to Malin Head datum;
- Gauge heights from the model were obtained by deducting the (current) station datum from the model produced water level;
- Therefore, the revised rating curve can be used to derive annual maximum flows from annual maximum gauge heights where the datum has not changed over the years.

However, for those stations where the datum changed over the years and the annual maximum gauge heights are referenced to the datum of the corresponding years, there are two primary options for using the revised rating:

- Use the gauge heights as provided (without any adjustment for the datum) or
- Adjust gauge heights with respect to the current datum.

The implications of the above options are as illustrated below with Station 08011 Duleek on the Nanny River (Figure 5-2). The overbank level (right bank) is at 18.38m OD Malin Head and above elevation 19.3m OD, there will be large amount of floodplain flow.

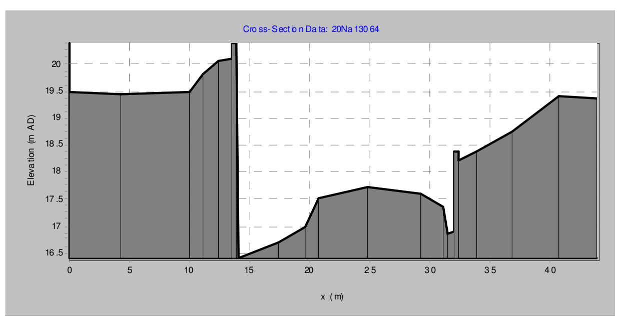

Figure 5-2: Section at Station 08011 Duleek on the Nanny River

The majority of the annual maximum water levels at this station are higher than 19.3m OD. For example, the highest recorded water level at this station was 19.98m OD on the 26th of August 1986 and the corresponding gauge height was 3.13m (i.e. a datum of 16.85mOD). The flood level represents a significant floodplain flow on both banks.

It is considered that a movement of 0.4m in the lowest level in the channel bed (i.e. not the whole section) would not result in a discernable change in water level from 19.98m OD for the event. This rationale is based on the flood level being predominantly governed by high flow in channel and out of bank geometry rather than low flow channel geometry.

If one uses the modified rating curve and the then gauge height of 3.13m without giving due consideration to the changed datum, this means that the flood water level for that event was only [16.437(current datum) + 3.13 =] 19.567m OD. On the other hand, a revised gauge height of 3.543m in relation to the current datum (19.98 - 16.437 = 3.543m), means the 26 August 1986 flood water level would have been the same irrespective of small movement of bed at the gauging station. It is considered that the latter assumption is more appropriate for the annual maximum flood regime, and the revised rating would produce more representative flood for that event.

Based on the latter assumption, for all stations which have no permanent weir and for which the zero datum changed over the years, the latest datum (used for rating review) was deducted from the series of available water levels to obtain revised series of gauge heights at the hydrometric stations. The revised gauge heights and the revised rating were used to obtain revised series of flows. The revised flow series was uploaded to the AquillaDSF and the revised annual maximum series was extracted.

There were some discrepancies between the annual maximum series of water level (gauge height) obtained from the instantaneous series and that from the annual maximum series (downloaded from www.opw.ie/hydro) at Station 08011 Duleek. For example, the AM series data at Station 08011Duleek showed gauge heights of 3.13m, 2.80m and 3.46m for the 26 August 1986, the 13 June 1993 and the 6 November 2000 extreme flooding events, whereas the data extracted from the instantaneous series showed the corresponding values as 3.0939m, 2.8087m and 3.5166m respectively. The Project Brief (page 12) suggests that, if discrepancies exist between the two data sets, the annual maximum values would typically be more reliable. Therefore, the data obtained directly from the annual maximum series was adopted for the statistical analysis.

For the OPW Station 08008 Broadmeadow, as there is a permanent weir, the annual maximum gauge height was used without any modification for up to the year 2007. The year 2008 annual maximum flood (for which annual maximum gauge height was not available) was extracted from the instantaneous series of water levels.

The Q_{med} value at all the nine gauging stations is presented in Table 5-4 below. The Q_{med} value of all stations used in the study is presented in Table B-2-1 in Appendix B.

Table 5-4: Q_{med} value at the study area gauging station

Gauging Station	River/Stream	Catchment area (km^2)	Record length (years)	Index flood, Q_{med} (m^3/s)	Specific Q_{med}	Standard error of Q_{med} (m^3/s)
08002	Delvin	37	24	4.40	0.273	0.32
08003	Broadmeadow	76.2	22	19.89	0.707	1.53
08005	Sluice	10.1	23	3.17	0.534	0.24
08007	Broadmeadow	34	21	8.16	0.540	0.64
08008	Broadmeadow	110	28	21.06	0.564	1.43
08009	Ward	62	15	4.97	0.207	0.46
08010	Garristown	1.13	13	0.620	0.564	0.06
08011	Nanny	181	28	48.38	0.884	3.29
08012	Ballyboghill	22.1	17	6.83	0.630	0.60

Note: Specific $Q_{med} = Q_{med}$ / (Catchment area)$^{0.77}$

It is observed from Table 5-4 that seven out of the nine stations in the study area have specific Q_{med} value higher than $0.5m^3/s$, whereas Station 08002 Naul on the Delvin River and Station 08009 Balheary on the Ward River have smaller than average specific Q_{med} values.

The reasons for the smaller Q_{med} values at Station 8002 Naul could be due to the inability of the gauge to record high water levels (see Section C1.1 in Appendix C).

The median flow Q_{med} at Station 08009 Balheary on the Ward River was found to be very low. The specific Q_{med} value (i.e., Q_{med} / $A^{0.77}$) at this station is only 0.207m^3/s, whereas the neighbouring Broadmeadow catchment (Station 08008 Broadmeadow) has specific Q_{med} value of 0.564m^3/s. All the annual maximum gauge heights at this station are of less than 1.0m except the 12 June 1993 gauge height which was 1.25m. The possible reasons for the low value of specific Q_{med} at this station are explained in Section C1.6 in Appendix C (absence of records for the major flood events).

At Station 08003 Fieldstown on the Broadmeadow River, the data quality for the most of the instantaneous gauge heights is assigned as "U", this means unchecked values. The high flow regime at this station appears to have been affected by the downstream bridge, as described in Section C1.2 in Appendix C. Therefore, from the quality point of view, the annual maximum series data of this station was not used for further analysis.

5.3.3. Standard error of Q_{med}

As part of the ongoing Flood Studies Update (WP2.2), a methodology has been proposed for the estimation of standard error (*se)* of median flood (Q_{med}), quantile estimate (Q_T) and growth factor (X_T) for flood estimation in Ireland (Cunnane, 2009). The methodology also proposes percentage *se* values for growth factor X_T, and for quantile estimate Q_T, for various return periods (T = 5, 10, 25, 50, 100 and 500 years) for the GEV and EV1 based estimates. The FSU methodology has been applied for the estimation standard error (*se*) of Q_{med}, of growth curve and also of the quantile estimates (see Section 5.4.4).

The standard error *se* of an estimate Q_T is an indication of how reliable that estimate is, and defined as;

Se (Q_T) = Standard deviation of all the possible set of Q_T values

Accordingly, the standard error, adapted to Irish Annual Maximum flood conditions, is:

Se (Q_{med}) = $0.36/\sqrt{N} * Q_{med}$

The standard error of Q_{med} for the nine annual maximum series is calculated accordingly and presented in the last column of Table 5-4.

5.4 Pooled hydrograph growth curve

5.4.1. Growth curve rationale

The Flood Studies Report recommended growth curve for Ireland has been compared to that observed at gauges in the Greater Dublin Area by various studies. Bruen *et al* (2005) suggests that the Flood Studies Report significantly under predicts extreme flows in the Dublin and Mid Eastern Region. The Greater Dublin Strategic Drainage Study (GDSDS, 2005) recommends a modified growth curve for the Greater Dublin area.

Based on the current uncertainty in the FSR Ireland growth curve and in the light of the growth curve proposed for the Greater Dublin area by the GDSDS, a statistical analysis of annual maximum series at the hydrometric stations in the FEM FRAM study area has been undertaken. For this purpose the hydrometric data of neighbouring catchment surrounding the FEM FRAM study area, namely, Hydrometric Area 07 and Hydrometric Area 09 have also been used.

5.4.2. Selection of pool group

The hydrological statistical analysis undertaken is based on the L-Moments method of fitting the available data to a suitable statistical distribution, as presented in the FEH and Hosking *et al* (1997). Utilising the L-Moments technique to the study data sets, the most representative distribution is determined by the proximity of site L-Moment ratios to the theoretical distribution.

The length of record of annual maximum series at the eight hydrometric stations in study area varies from 13 to 28 years. The total number of annual maxima in these eight AMSs is only 169, which is considered insufficient for undertaking statistical analysis using regional pooling of data method (refer FEH Vol 3 (IOH, 1999)). To augment this low level of data in the study area, annual maximum series from the neighbouring gauging stations (from Hydrometric Areas 07 and 09) were collected from the OPW and EPA. From the review of these data, it was found that some stations have very short length of record and some have only pre-1970 data. As the AMSs from the study area consisted of post-1970 data, only those AMSs from the neighbouring stations were selected which consisted of post-1970 hydrometric data of at least 14 years or longer record (refer to Section 5.3.2). Eight annual maximum series from neighbouring catchments were found to satisfy these criteria, which are Station 07002 Killyon, Station 07005 Trim, Station 07006 Fyanstown, 07009 Navan Weir, Station 07010 Liscartan and Station 07012 Slane Castle from HA 07 and Station 09001 Leixlip and Station 09002 Lucan from HA 09. Thus the total number of AMSs selected for the pooling group analysis is 16 and the total number of annual maxima is 507. Details of these annual maximum series are presented in Table B-2-1 in Appendix B.

The similarity (homogeneity) of the data for a regional pooling group method is measured on the basis of geographical proximity and catchment similarity. According to FEH, the pooling groups based on catchment similarity are more homogeneous. The present study area (HA 08) is surrounded by the Irish Sea to the east and by HA 07 and HA 09 to the north, west and south. Inclusion of hydrometric data from the catchments beyond HA 07 and HA 09 are considered not as directly representative of the study area due to their inland location and prohibitive in their use due to the absence of a corrected national data set. The FEH also suggests using at least 5*T number of data for the estimation of T year returns period floods from pooling method. As the total number of annual maxima at these 16 stations is 507, it is preferable that all the data is used for estimating peak flow values up to and beyond the 100-year return period events. Therefore catchment similarity tests were not carried out for the present study.

In accordance with the FEH V3 6.5 check for pooling group discordancy, a visual review was undertaken of L-moment ratio similarity. For this purpose, an L-moment ratio diagram was prepared for individual AMS data as well as for the group of stations in HA 08 and also for the group of all 16 AMSs (See Figure 5-3).

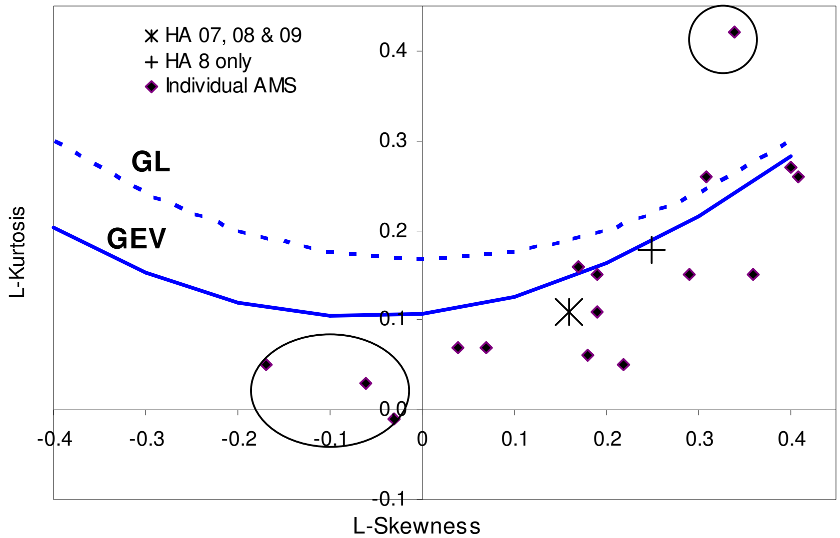

Figure 5-3: L-moment ratio diagram (circled AMSs were excluded from pooled group)

The L-moment ratio diagram (Figure 5-3) demonstrated that the most discordant L-moment ratio were Station 08009 Balheary (located at extreme top right of the diagram) and Station 07005 Trim, Station 07006 Fyanstown and Station 07010 Liscartan (located at extreme bottom left). L-moment ratios of these four AMSs were considered unrepresentative of the group cluster, and were also excluded from the pooling group method of regional analysis. It is noted that the AMS of Station 08009 Balheary on the Ward River, which has a smaller specific Q_{med} value in comparison to the other stations in the study area, lies away from the group cluster on the L-moment ration diagram. Based on the L-moment ratio similarity, only 12 AMS (total number of annual maxima being 393) were finally used for the pooling group analysis. These include seven AMSs from HA08 (Station 08002 Naul, 08005 Kinsaley Hall, Station 08007 Ashbourne, Station 08008 Broadmeadow, Station 08010 Garristown, Station 08011 Duleek and Station 08012 Ballyboghill), two AMSs from HA09 (Station 09001 Leixlip and Station 09002 Lucan) and three AMSs from HA07 (Station 07002 Killyon, Station 07009 Navan Weir and Station 07012 Slane Castle). The 12 annual maximum series used for the regional analysis is presented in Table B-2-2 in Appendix B.

Figure 5-3 also shows that the L-moment ratios of 11 out of 12 AMSs are close to the theoretical L-moment ratios of GEV distribution. The weighted average L-moment ratio of the group of AMS is close to that of GEV distribution. Therefore, it is considered that GEV distribution is representative of the AMS data considered for a pooling group analysis.

5.4.3. Study area growth curve

The regional pooling group of the 12 stations was analysed using the GEV distribution and method of L-moments (ref: Vol 3 of FEH). The analysis sought to develop regional growth factors indexed to the Q_{med}. The regional growth curves obtained from the pooling group analysis together with the corresponding growth curves of FSR and Greater Dublin Strategic Drainage Study (both indexed to Q_{med}) are presented in the Table 5-5 and Figure 5-4.

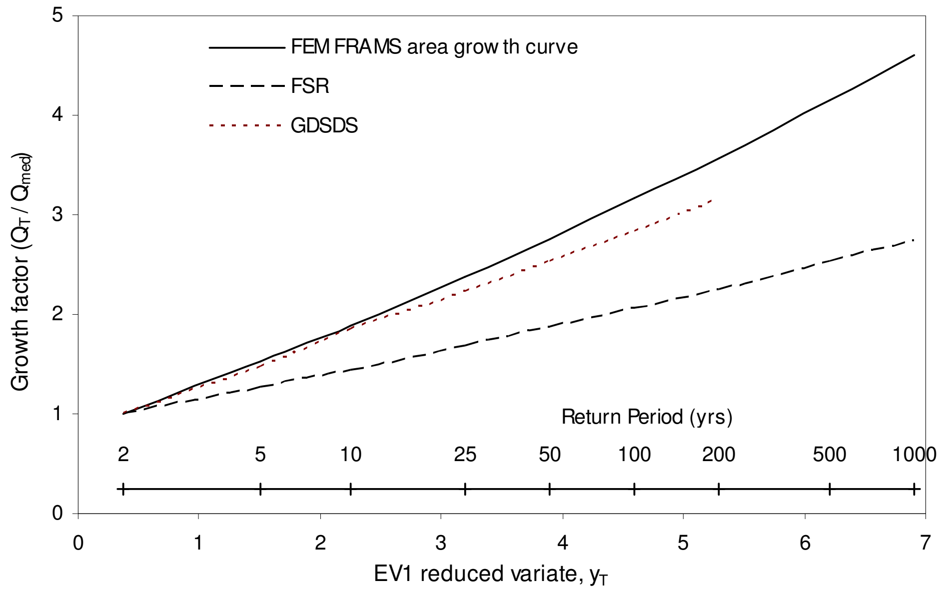

Figure 5-4: Study growth curve compared with those of FSR and GDSDS

Table 5-5: Study growth factor compared with FSR and GDSDS (all indexed to Q_{med})

Return Period (yrs)	**2**	**5**	**10**	**25**	**50**	**100**	**200**	**1000**
AEP	50%	20%	10%	4%	2%	1%	0.5%	0.1%
FEM FRAMS	**1.00**	**1.52**	**1.89**	**2.38**	**2.76**	**3.16**	**3.57**	**4.60**
GDSDS	1.00	1.47	1.85	2.23	2.53	2.83	3.15	
FSR (Ireland)	1.00	1.26	1.44	1.68	1.86	2.06	2.25	2.74

It is observed from Table 5-5 and Figure 5-4 that the study area growth factor is close to that of GDSDS for up to 10year return period (10% AEP). For higher than 10-year return period, the study area growth factor is consistently higher than that of GDSDS.

5.4.4. Confidence interval

The uncertainties in the estimated flood arise from, namely, uncertainty in the growth curve and uncertainty in the Q_{med} estimates.

The FEH, Volume 3, Section 17.5, lists range of factors due to which uncertainty in the pooled growth curve can arise. A general indication of the level of uncertainty associated with the growth curve is given by the pooled uncertainty measures (PUM). The PUM summarises the average difference between pooled and site growth factors at the target return period. In FEH, PUM is evaluated for two target return periods (20 and 50 years), but not for greater return periods because 20-year records do not provide sufficiently accurate estimates of corresponding growth factors (FEH Volume 3, Section 16.3.3).

The FSU methodology has been applied for the estimation standard error (*se*) of the growth curve as well as for the quantile estimates (refer to Section 5.3.3).

The 95%ile confidence interval of the study area growth curve is then estimated using the following relationship,

X_T (95%ile) = $X_T \pm 1.96 * se(X_T)$

The study area growth curve with the 95%ile confidence limit is shown in Figure 5-5.

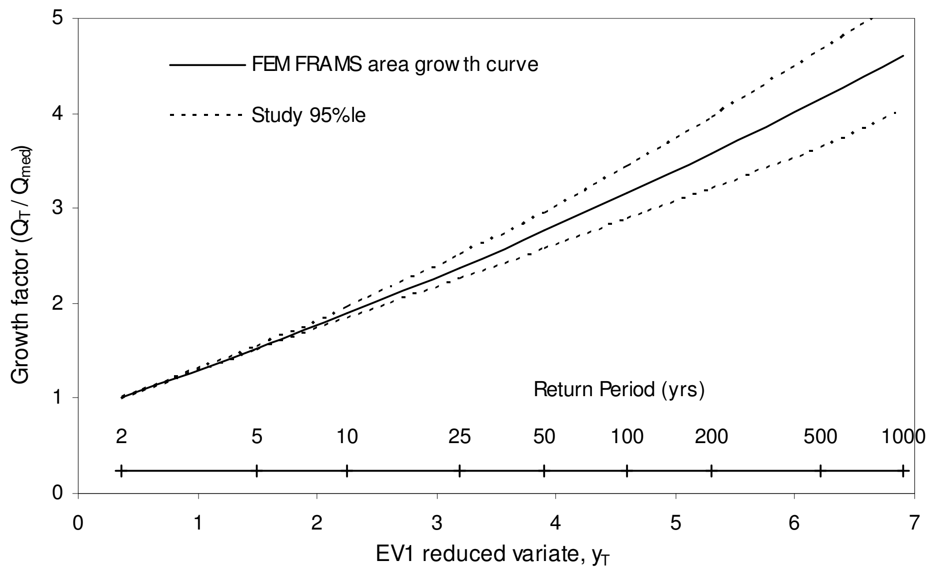

Figure 5-5: Study growth curve with 95%ile confidence limit

Similarly, to calculate the confidence interval of quantile estimates, the standing error (*se*) was first calculated using the values proposed in FSU (refer to Section 5.3.3) for estimating *se* of quantile estimates for EV1 and GEV distribution as appropriate. Then the 95%ile confidence interval of quantile estimates was calculated using the relationship:

Q_T(95%ile) = $Q_T \pm 1.96 * se(Q_T)$

5.4.5. Design flow at hydrometric stations

At each of the stations in the study area, the quantile estimates of 2, 5, 10, 25, 50, 100, 200 and 1000 years return period were estimated using the at-site growth curve and from the study area growth curve.

The annual maximum series was plotted (plotting position) against EV1 reduced variate together with the frequency plots derived from at-site growth curve (EV1 based) and from study area growth curve. The 95%le confidence limit of the design flows, estimated using the methodology mentioned in Section 5.4.4, are also shown on these plots. The flood frequency plots for all the stations are presented in Appendix C2 and that for Station 08012 Ballyboghill on the Ballyboghill River is presented in Figure 5-6.

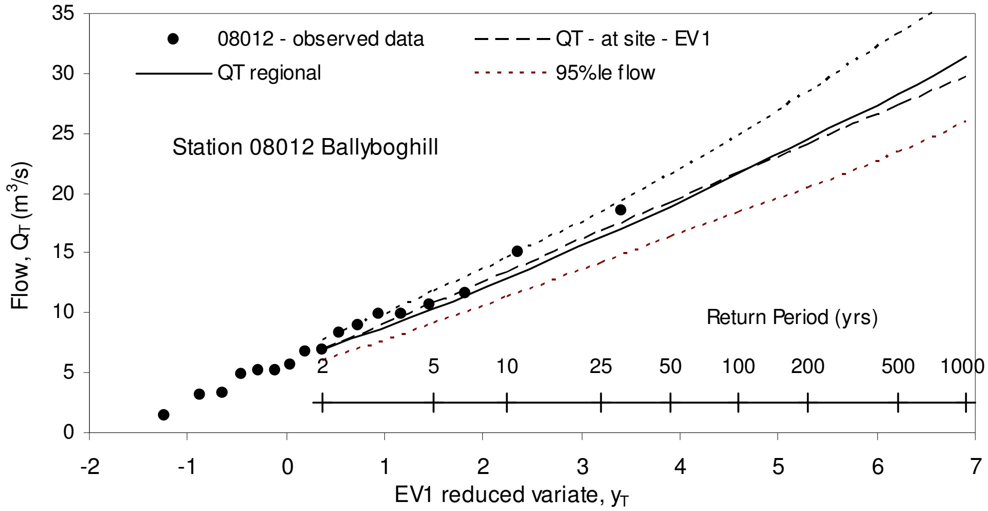

Figure 5-6: Frequency plot of Station 08012 Ballyboghill on the Ballyboghill River

In Figure 5-6, the thick line at the middle represents the frequency curve from study growth curve, the dotted line represents the frequency curve from at-site growth curve (EV1 distribution based) and the two dotted lines at the extreme end represent the 95% confidence intervals for the design flood values.

It is observed from Figure 5-6 that both frequency curves (from at-site and study area growth curve) are quite close to each other. These curves are within the 95%le confidence limits. The two largest annual maximum flood values, which are slightly away from the study growth curve, are also within the 95% confidence limits.

The design floods, 95%le confidence limits and frequency plots for all stations in the study area (except Station 08003 Fieldstown) are presented in Appendix C2. Summary of design floods at these stations together with confidence limits are shown on Table 5-6.

Table 5-6: Design flood of various return periods with 95%ile confidence limits

Station	T (years)->	2	5	10	25	50	100	200	1000
	AEP	50%	20%	10%	4%	2%	1%	0.5%	0.1%
08002	Q_T	**4.4**	**6.7**	**8.3**	**10.5**	**12.2**	**13.9**	**15.7**	**20.3**
	Lower 95%le	*3.9*	*5.9*	*7.3*	*9.1*	*10.5*	*11.8*	*13.2*	*16.7*
	Upper 95%le	*4.9*	*7.5*	*9.4*	*11.8*	*13.8*	*16.0*	*18.3*	*23.8*
08005	Q_T	**3.2**	**5.4**	**6.9**	**8.7**	**10.1**	**11.5**	**12.9**	**16.0**
	Lower 95%le	*2.8*	*4.8*	*6.0*	*7.7*	*8.8*	*10.0*	*11.2*	*13.9*
	Upper 95%le	*3.5*	*6.0*	*7.7*	*9.8*	*11.4*	*13.0*	*14.5*	*18.1*
08007	Q_T	**8.2**	**12.4**	**15.4**	**19.4**	**22.6**	**25.8**	**29.2**	**37.6**
	Lower 95%le	*7.1*	*10.9*	*13.5*	*17.0*	*19.5*	*21.9*	*24.4*	*31.0*
	Upper 95%le	*9.2*	*14.0*	*17.4*	*21.9*	*25.6*	*29.6*	*33.9*	*44.1*
08008	Q_T	**21.1**	**32.1**	**39.8**	**50.1**	**58.2**	**66.6**	**75.3**	**96.9**
	Lower 95%le	*18.4*	*28.1*	*34.8*	*43.8*	*50.3*	*56.6*	*63.1*	*79.9*
	Upper 95%le	*23.7*	*36.1*	*44.8*	*56.5*	*66.1*	*76.5*	*87.5*	*113.9*
08009	Q_T	**13.1**	**19.9**	**24.7**	**31.1**	**36.1**	**41.3**	**46.7**	**60.2**
	Lower 95%le	*11.4*	*17.4*	*21.6*	*27.2*	*31.2*	*35.2*	*39.1*	*49.6*
	Upper 95%le	*14.7*	*22.4*	*27.8*	*35.1*	*41.0*	*47.5*	*54.3*	*70.7*
08010	Q_T	**0.62**	**0.94**	**1.17**	**1.48**	**1.71**	**1.96**	**2.22**	**2.85**
	Lower 95%le	*0.54*	*0.83*	*1.03*	*1.29*	*1.48*	*1.67*	*1.86*	*2.35*
	Upper 95%le	*0.70*	*1.06*	*1.32*	*1.66*	*1.95*	*2.25*	*2.58*	*3.35*
08011	Q_T	**48**	**74**	**91**	**115**	**134**	**153**	**173**	**223**
	Lower 95%le	*42*	*65*	*80*	*101*	*115*	*130*	*145*	*184*
	Upper 95%le	*54*	*83*	*103*	*130*	*152*	*176*	*201*	*262*
08012	Q_T	**6.8**	**10.4**	**12.9**	**16.3**	**18.9**	**21.6**	**24.4**	**31.4**
	Lower 95%le	*6.0*	*9.1*	*11.3*	*14.2*	*16.3*	*18.4*	*20.4*	*25.9*
	Upper 95%le	*7.7*	*11.7*	*14.5*	*18.3*	*21.4*	*24.8*	*28.4*	*37.0*

5.5 Calibration hydrology

5.5.1. Selection of calibration events

For hydraulic model calibration, observed stage data are required at the gauging stations, and ideally other observed flood level data e.g. wrack marks, at other locations along the modelled reach. The nine hydrometric stations in the study area are located on six rivers, namely Sluice, Broadmeadow, Ward, Ballyboghill, Delvin and Nanny; therefore it will only be possible to calibrate these six hydraulic models. Out of the nine gauging stations, three major stations (Station 08005 Kinsaley Hall on the Sluice River, Station 08009 Balheary on the Ward River and Station 08008 Broadmeadow on the Broadmeadow) are located close to the downstream boundary of the respective hydraulic model.

Extensive information on flooding in the study area is available for the recent events, in the form of descriptions of the flooding with photographs showing the extent of flooding. However, seven out of the nine hydrometric stations in the study area were closed between 1995 and 2001, therefore it was difficult to identify events that had both observed hydrometric data plus other observed flood level data e.g. photographs, flood extents. The calibration events identified for each of the rivers are shown in Table 5-7.

Table 5-7: Selected calibration events for the gauged catchments

Station	River	Date of flood	Other flood level data
08007 and 08008	Broadmeadow	26/08/1986	Water levels at Station 08007 = 63.333m OD and at Station 08008 = 7.457m OD Malin Head
08011	Nanny	06/11/2000	Water level upstream of the Ashbourne Road Bridge = 20.81 to 20.90 m OD; upstream of the Drogheda Road Bridge = 20.04 to 20.16m OD; at Beaumont Bridge = 14.6m OD (Malin Head). Photographs showing extent of flood.
		26/08/1986	Hurricane Charlie, photographs showing the extent of flood.
		12/06/1993	Photographs showing the extent of flood.
08012	Ballyboghill	26/08/1986	Photograph showing the extent of flood.

5.5.2. Calibration methodology

Flood hydrographs for the events listed in Table 5-7 have been extracted using the revised rating curves. As the application of the hydrograph at one location (just upstream of the gauging station) would not enable calibration of the model further upstream of the gauging station, an indirect approach will be used to apply distributed inflows at upstream reaches of the river. This flow distribution will be carried out using scaled ISIS FSSR 16 boundary units.

For a selected flood event, the ISIS FSSR16 boundary units with a return period higher than the return period of the calibration event will be applied to the hydraulic model. The (routed) flow in the hydraulic model at the gauging station will be compared with the observed flow at the gauge, and the hydrograph scaling parameters in the FSSR 16 boundary units will be adjusted until the flow in the hydraulic model at the gauging station matches the observed flow at the gauge. Once the model flow matches the observed flow, the hydraulic model will be calibrated to the observed water levels at the gauging station and at other locations along the modelled reach.

5.6 Return periods of the recent flooding events

The approximate return period for the three largest events at the 6 hydrometric stations are presented in Table 5-8. The return period of these flooding events are evaluated based on the at-site flood frequency curve obtained from EV1 distribution.

Table 5-8: Return period of the major flood events at the study area hydrometric stations

Gauging Station	River/Stream	Major flood events	Peak flow m^3/s	Approx Return period (years)
08002	Naul on the Delvin River	28/12/1978	14.5	≈100
		06/11/2000	12.6	≈ 50
		13/11/2002	9.8	10 - 20
08005	Kinsaley Hall on the Sluice River	06/11/2000	11.5	≈ 100
		11/06/1993	9.9	25 – 50
		27/12/1978	6.7	< 10
08007	Ashbourne on the Broadmeadow River	13/11/2002	31.8	> 100
		26/08/1986	17.9	10 - 20
		21/01/1980	16.1	≈ 10
08008	Broadmeadow on the Broadmeadow River	13/11/2002	43.7	25 - 50
		21/01/1980	39.3	10 - 25
		06/11/2000	32.1	5 - 10
08011	Duleek on the Nanny River	26/08/1986	88	≈ 25
		6/11/2000	85	10 - 25
		14/11/2002	72	5 - 10
08012	Ballyboghill on the Ballyboghill River	26/08/1986	18.5	25 - 50
		06/11/1982	15.1	10 - 25
		23/11/1990	11.7	5 - 10

5.7 Sensitivity to change in catchment parameters

Design flow rates are sensitive to changes in both catchment runoff parameters and rainfall parameters. In the FEM FRAM study, the ISIS FSSR 16 boundary units, which comprise of catchment characteristics, rainfall parameters and urban factors are extracted for the 270 sub-catchments. The accumulated total (routed) inflows from these sub-catchments will be reconciled with the design floods estimated at the hydrometric stations, using iterative simulations in the hydraulic models, by changing the scaling factor globally (refer to Section 6.4). These iterative simulations are equivalent to sensitivity analyses and hence no separate sensitivity test is to be carried out. The results of the iterative simulations necessary for reconciliation of the flows at the gauging stations will be reported in the hydraulic report.

5.8 Recommendations for re-installation of hydrometric stations

As discussed in Section 2.3 above, the OPW provided hydrometric data of two stations and the EPA provided data of ten stations in the study area. The two OPW stations in the study area are currently operational, but all ten of the EPA stations were closed between 1995 and 2001. Out of the ten EPA stations, one station (namely, Station 08007 Ashbourne) is in the administrative area of Meath County Council. The other nine stations were previously in the administrative area of Dublin County Council and are subsequently in the administrative area of Fingal County Council, when FCC was established in 1994. According to FCC Report (2008), these gauging stations have not been in operation for some years due to a variety of reasons, mainly due to uncertainty as to who is responsible for these stations.

The hydrological analysis and calibration of the hydraulic models are affected due to the unavailability of the hydrometric data and useful information about the recent flooding events in the study area. Therefore it is recommended to re-install these closed stations in the study area in order to record the valuable hydrometric information which would be useful for the forecasting of floods in the future.

It is understood that Fingal County Council is considering reopen these hydrometric stations in a phase-wise basis. Based on the 'FCC Report on Hydrometric Stations (2008)' and the EPA comments on the Preliminary Hydrology Report, Halcrow Barry has prepared a priority list for re-installing gauging stations on the most critical rivers and at strategic locations. The full list of hydrometric stations in the study area (HA 08) and the recommended priorities are presented in Table B-4 in Appendix B. A summary of the recommendations is presented below.

- Two stations, namely Station 08008 Broadmeadow on the Broadmeadow River and Station 08011Duleek on the Nanny River, which are currently operational in the study area, should be maintained.
- Three stations, namely, Station 08002 Naul on the Delvin River, Station 08010 Garristown on the Garristown Stream and Station 08012 Ballyboghill on the Ballyboghill River are being upgraded by FCC. New weirs were constructed at Station 08002 Naul (new) and Station 08010 Garristown. According to the EPA, data loggers were installed at Station 08010 Garristown on 18 November 2009 and at Station 08002 Naul (new) on 14 December 2009. The Station 08012 Ballyboghill should also be made operational as soon as possible.
- Another thee stations, namely, Station 08005 Kinsaley Hall on the Sluice River, Station 08009 Balheary on the Ward River and Station 08007Ashbourne on the Broadmeadow River are recommended as the first priority stations for re-installation
- Further four stations, namely, Station 08006 Hole in the Wall on the Mayne River, Station 08003 Fieldstown on the Broadmeadow River, Station 08004 Owen's Bridge on the Ward River and Station 08014 Skerries on the Mill Stream are recommended as the second priority stations for re-installation
- The existing locations of Station 08005 Kinsaley Hall on the Sluice River and Station 08014 Skerries on the Mill Stream have access problem. The location of Station 08003 Fieldstown on the Broadmeadow River is affected by the downstream bridge during a high flow regime. The location of Station 08009 Balheary on the Ward River is close to the tidal extent and it could be affected by coastal flooding in the future. The location of Station 08004 Owen's Bridge on the Ward River is now a reservoir. Therefore, new locations will have to be identified for these five stations.

6. Integration of hydrology and hydraulic modelling

6.1 Introduction

The FEM FRAM study area consists of a total of 24 rivers and streams and three estuaries. One of them, the Mornington River is not being modelled as part of this study (as it is part of a separate study), thus giving the total number of rivers and streams to be modelled as 23.

As described in Section 1.2, only certain sections of the rivers and streams in the study area have been designated as being HPWs or MPWs. In order to represent the hydrological processes in sufficient detail to enhance the hydraulic model outputs, the HPWs and MPWs in the study area have been sub-divided into a number of smaller sub-catchments.

The design inflows at sub-catchment level have been calculated using the FSSR 16 and Institute of Hydrology Report No. 124 Unit Hydrograph (UH) method. To facilitate this, a tool has been developed, i.e. the ISIS FSSR16 boundary unit, which is capable of producing hydrographs of various AEP events using FSSR16/IOH UH methods. ISIS FSSR16 boundary units, which comprise catchment characteristics, soil index, rainfall parameters and urban factors, will be used as the inflow boundaries in the hydraulic models.

The IOH Report No. 124 - Flood estimation for small catchments: 'Section 6 - Analysis of flood response times' provides a methodology for the estimation of peak flow for ungauged catchments using the unit hydrographs method. The UH method does not involve the calculation of Q_{bar} or Q_{med} but it directly estimates the hydrograph peaks. The IOH 124 equations have been used for estimating the time to peak for small sub-catchments (areas less than 25km^2). For sub-catchments with areas greater than 25km^2, the FSSR 16 method is used. The ISIS 'FSSR 16 boundary' tool has the option to select either of these two methods.

The IOH Report No. 124 - 'Section 7: Mean annual flood' suggests a modified equation for the estimation of Q_{bar} using catchment characteristics for small catchments. The hydrological analysis for FEM FRAMS estimates Q_{med} directly from the annual maximum series, but not from the catchment characteristics. Thus the Q_{bar} is not involved in the FEM FRAMS hydrological analysis.

6.2 Sub-catchments

6.2.1. Sub-catchment nodes

The sub-catchment nodes (downstream extent of each sub-catchment) are located as follows:

- at every hydrometric station within the study area;
- near the upstream and downstream end of every HPW and at no grater than 2km increments along HPWs;
- near the upstream end of every MPW and at significant tributary junctions.

The size of the catchments in the study area ranges from a little more than 1km^2 (e.g. Rush West Stream) to 181km^2 (the Nanny River). Satisfying the above criteria required just two sub-catchments for Rush West Stream, whereas 58 sub-catchments were required for the Broadmeadow River. Based on the above criteria, the total number of sub-catchments in the study area is 270. Each sub-catchment has been provided with a unique identification code. The first three letters of the code represent the river and the following number is the identification of the individual sub-catchment. For example, SLU_03 represents the third sub-catchment from the most downstream end of the Sluice River.

The number of sub-catchments in each hydraulic model is shown in Table 6-1 and the sub-catchment locations and boundaries are shown in Figures 4.1 to 4.8 in Appendix A.

Table 6-1: Number of sub-catchments in each hydraulic model

Mayne River (MAY) - 14	Jone's Stream (JON) – 4
Sluice River (SLU) – 16	Rush Town Stream (RUT) – 4
Gaybrook Stream (GAY) – 6	Rush Road Stream (RUR) – 2
Broadmeadow River (BRO) – 58	Rush West Stream (RWS) – 2
Ward River (WAR) – 22	St Catherine's Stream (CAT) – 4
Lissenhall Stream (LIS) – 7	Mill Stream (MIL) – 8
Turvey River (TUR) – 5	The Bracken River (BRA) – 14
Ballyboghill River (BAL) - 10	Delvin Stream (DEL) – 22
Corduff River (COR) – 10	Mosney Stream (MOS) – 6
Nanny River (NAN) – 37	Brookside Stream (BSS) – 3
Baleally Stream (BAY) - 6	Balbriggan North Stream (BNS) – 6
Bride's Stream (BRI) - 4	**Total = 270**

6.2.2. Sub-catchment boundaries

The boundaries of each catchment and sub-catchment were initially delineated using the EPA hydro DTM and the GIS automation tool (HEC-GeoHMS). At some inland locations, the external boundary of the FEM FRAM study area, obtained from GIS automation, did not match with the study area boundary identified in the Project Brief. The modified external boundary (inland) of the study area was confirmed with the OPW.

The boundaries of some of the sub-catchments obtained using GIS automation (and EPA hydro DTM) did not match with the ground conditions, i.e. the sub-catchment boundaries crossed over some of the streams. Similarly, the surface water drainage networks divert surface water from some sub-catchments to other sub-catchments. Therefore, the sub-catchment boundaries were manually corrected based on the information received from the survey data, latest OSi maps, information received from the EPA (catchment boundary), surface water networks in the urban areas including that of Dublin Airport area and some site visits.

6.2.3. Sub-catchment characteristics

Methodology

An in-house GIS automation tool (HEC-GeoHMS) was used to define sub-catchment characteristics, aided by manual checking. The sub-catchment characteristics, soil index and rainfall parameters for each of the sub-catchments were extracted as follows:

River centreline: The blue lines from OSi maps (1:50,000 scale) were used as the river centreline.

Catchment area: Calculated directly from the sub-catchment boundary generated from GIS automation and corrected manually using the OSi Map, survey data, EPA GIS layers, SW drainage networks and site visits.

Mean Stream Length (MSL): The mean stream length (MSL) at each sub-catchment level was extracted from the 1:50,000 OSi maps (blue lines).

Mean Slope (S1085): The mean stream slope was calculated from the elevation data, taken at 10% and 85% of the stream length from the EPA-20m hydro DTM.

URBAN Factor: The urban areas were digitised from the 2007 1:50,000 Discovery Maps, the urban areas in the vector maps were added (DXF files in scales 1:1,000; 1:2,500 and 1:5,000) and also new urban zones obtained from Google Earth were included.

SOIL Index: This was calculated using the Winter Rainfall Acceptance Potential (WRAP) from FSR Volume V, Figure I.4.18 (I) and using the corresponding equation of FSSR 16 UH method.

M5-2day, M5-25 day: Extracted from the FSU depth duration frequency model received from the OPW.

Jenkinson's ratio r: Extracted from the GIS layer of Jenkinson's ratio received from the OPW

Design storm duration: Calculated using the equations in FSSR 16 UH method. The storm duration was optimised using iterative simulation in hydraulic modelling (see Section 6.4).

Extraction of MSL and S1085

There are three types of sub-catchments in the study area (refer to Figure 6-1 overleaf), namely

- Upstream catchments (e.g. COR_09)
- Mid-catchments with a dominant tributary (e.g. COR_07, COR_05 and COR_03_A1)
- Mid-catchments without a dominant tributary (e.g. COR_01 and COR_02)

MSL and S1085 are derived from the longest stream contained within the sub-catchment boundary as defined by the 1:50,000 mapping. The approach used the consistent rule (refer to Section 4.2.2 of Volume I of Flood Studies Report (NERC, 1975)) in defining FSSR16 MSL and S1085 parameters for all of the above types of catchments.

Figure 6-1: Sub-catchments of the Corduff River

6.3 Advantages and limitations of ISIS FSSR 16 units

Advantages of ISIS FSSR 16 boundary units

Use of the ISIS FSSR 16 boundary units to generate inflow at sub-catchments offers several advantages:

- Based directly on industry standard FSR and IOH 124 methodologies
- The FSSR 16 UH method is being used not just for stand alone estimation for design inflows, the total flow (routed) from all the sub-catchments will be reconciled with the design flood estimated using the statistical method; therefore, the FSSR 16 UH method is essentially being used for internal redistribution of design inflows at sub-catchment level, as the total flow at the gauging stations will be reconciled with the design flood from the statistical method
- From the sensitivity check of S1085 slope at the 100-year peak flow, it was observed that by doubling the mean slope, the peak flow only increases by 5 - 10%. This lack

of sensitivity is due to the S1085 being used in the Tp calculations as opposed to runoff calculations. It is considered that this sensitivity of 5 - 10% is within the confidence limits for the 100-year case. Furthermore, flows will be reconciled at the gauging stations, hence these differences are expected to be reduced.

- The topography of the FEM FRAM study area is relatively flat and the modelled catchments are relatively small. It is considered that the longest stream length characteristics are appropriately representative of catchment topography.
- A consistent methodology has been used for extracting all the catchment characteristics, according to the FSSR 16 UH method. For some flat catchments, if the calculated slope is flatter than 0.019% (i.e., 1 in 5263), the minimum slope of 0.019% is used.
- The Institute of Hydrology Report No 124 compares DTM-derived MSL and S1085 characteristics with those derived from 1:25,000 mapping. Figure 4.5 of the IOH 124 demonstrates that the difference between DTM and 1:25,000 estimates of S1085 is negligible, but the difference in MSL is significant (Figure 4.4 of IOH 124). Therefore, any deviation from FSR-stated catchment characteristic definitions would render the parameters of the FSSR16/IOH124 regression equations invalid.

Therefore, it is considered that the approach of using FSSR 16 UH method for estimating design inflow at sub-catchments level described above is appropriate for the purpose of this study.

Limitations of ISIS FSSR16 boundary units

The ISIS FSSR 16 boundary units have been created using the catchment characteristics mentioned above. These units can be imported directly to the corresponding sub-catchment nodes in the hydraulic model.

The following limitations were encountered with the ISIS FSSR16 boundary units:

- The urban factor cannot be more than 0.808
- Catchment area limit is from 0.038km^2 to 9,868 km^2
- The MSL range from 0.27km to 293km
- The mean channel slope (S1085) ranges from 0.19m/km (1 in 5263 or 0.019%) to 118 m/km (1 in 8.47 or 11.8%)

The sub-catchment nodes were adjusted to fit in the above criteria. For some of the most downstream sub-catchments the minimum slopes were found to be less than 0.19m/km, so the minimum allowable slope of 0.19m/km was adopted.

6.4 Reconciliation of flows at hydrometric stations

The design inflow estimated using the FSSR 16 and IOH UH method at each node is applied to the hydraulic model as follows:

- For a sub-catchment at the upstream end of the modelled reach, it will be applied as a point inflow to the first node at the upstream end of the reach

- For a sub-catchment across a river reach where there is a non-modelled tributary, it will be applied as a point inflow to a single node at the confluence
- For sub-catchment across a river reach where there are not any tributaries, it will be applied as a lateral inflow which will act as a distributor to apportion the inflow along the river reach as opposed to applying a point inflow to a single node

For both gauged and ungauged catchments, the design storm durations in the FSSR 16 boundary units will be optimised using iterative simulation in the hydraulic model. The adopted design storm duration will be the one which will produce the highest water level in the watercourses at some strategic locations. The design storm duration will be optimised for all watercourses being modelled.

For the gauged catchments, the total (routed) inflows at hydrometric stations generated from the FSSR 16/IOH 124 UH methods at sub-catchment levels will be reconciled with the return period floods estimated from the statistical method. The steps involved in the reconciliation methodology is summarised below.

I. In case of a gauged watercourse, the total (routed) inflow at a hydrometric station generated from the sub-catchment will be compared with the design peak flow value from the statistical method for a given AEP. If the two flow values at the station do not match, the FSSR 16 UH based inflows will be scaled (up or down as necessary) through the global scaling of the sub-catchment hydrographs. The hydraulic model will be re-run and the total (routed) inflow at the station will again be compared with the design peak flow from the statistical method. This process will be repeated until the flows from the two methods match each other. The scaling factor which enables this matching is adopted as the design scaling factor for the AEP for the station.

II. Step I is repeated for all gauged watercourses for two AEP events, namely, for 50% (equivalent to the 2 year return period) and 1% (equivalent to the 100 year return period). The scaling factors for the other AEP events at a station will be calculated from the interpolation / extrapolation of the scaling factors of the 50% and the 1% AEP events at that station.

III. The scaling factors for the ungauged catchments will be based on the results of the re-conciliation for the gauged catchments. The study area average scaling factor for each AEP events will generally be applied to the ungauged catchments.

As the hydraulic modelling is still ongoing, the final results of the scaling factors and of the sub-catchment design inflows will be reported in the Hydraulic Report.

7. Future environmental and climate change

7.1 Background

Future flood risk in the Fingal and East Meath catchments can be influenced by a number of drivers. These include changes in climate, land use, land management and urban growth. As these factors are likely to change over time it is important to appreciate how they could affect future flood risk across the catchments. To achieve this, it is necessary to test possible future scenarios to help in considering what protection levels may be required to protect against future flooding.

This section sets out the possible implications of climate change (Section 7.2), land use change (Section 7.3) and urban development (Section 7.4) on the hydrological processes in the FEM FRAM study area. Based on the outcome of the above analysis, two future flood risk management scenarios are proposed (Section 7.5). The potential impact of these future scenarios will be tested by hydraulic model simulations and will be reported in the Hydraulics Report.

7.2 Climate change

7.2.1. Introduction

The effects of future climate change on the rainfall pattern in Ireland and the catchments response to these in producing unusually high floods has been acknowledged by the extensive quantity of climate change research undertaken both in Ireland and in the UK. The noted Irish research on the effect of climate change includes those carried out by Sweeney *et al.* (2003), Sweeney and Fealy (2006), McElwain and Sweeney (2007), Irish Committee on Climate Change (2007), Royal Irish Academy (2007), the Community Climate Change Consortium for Ireland (McGrath et al, 2004), McGrath *et al.* (2005), McGrath and Lynch (2008). A review of climate change literature has been undertaken (See Appendix D), which considered a wide range of publications in Ireland and abroad.

All the above Irish research has widely predicted that the effects of future climate change in Ireland will have impacts on sea level, storm event magnitude and frequency, and rainfall depths, intensities and patterns. These impacts are likely to have significant implications for the degree of flood hazard, and hence flood risk in Ireland. Despite the significant effort and extensive research in Ireland and around the world, there remains a very significant degree of spatial, temporal and quantitative uncertainty as to how the Irish climate will change and what impact such change might have for flood hazard and risk in Ireland.

7.2.2. Guidance policy

Ireland

An adopted policy for the design of flood relief schemes and flood risk management measures, with respect to the impacts of potential changes in the climate, does not yet exist for Ireland. A provisional policy is in place, however, whereby predicted increases in flows and / or water levels are to be included where possible.

The current policy document 'Design Considerations of Possible Climate Change for Flood Risk Management Practice' (2006) requires the following:

- Sea level rise: climate change allowance to be added to design levels in all tidal situations; an additional allowance is to be added on the South Coast for ground level movement. It is not clear whether sea level changes as a result of localised storm surges should be treated specifically or whether only global average sea level rise should be considered. The allowance is to be considered as a component of the design water level and not as freeboard.

- Increase in flood flows:

    - Sensitivity-guided design - whereby the sensitivity of the design of a scheme to climate change is tested e.g. by testing the parameters subject to change, such as peak flow.

    - Design for enhancement - flood relief scheme designed so that defence levels/capacities can be increased/enhanced in the future.

    - Design for climate change – flood relief works designed to cope with predicted future conditions.

The literature review by Bruen (2003), commissioned by the OPW, looked at climate change on a regional scale in Ireland, particularly, likely change in river flows and extreme water levels in coastal areas, during the 21st century.

UK Defra guidance, England & Wales (2006)

Other policy information has been sought for the FEM FRAMS from guidance recently adopted within the UK by the Department for Environment and Rural Affairs (Defra).

Defra has produced guidance on impacts of climate change for operating authorities (i.e. Environment Agency, Local Authorities and Internal Drainage Boards). Several documents exist to inform climate change consideration: The Flood and Coastal Defence Project Appraisal Guidance - overview (FCDPAG1), sets out the basis for considering climate change; detailed sea level rise allowances are recommended in FCDPAG3; and FDCPAG4 also sets out advice on sensitivity testing.

Supplementary guidance to FCDPAG3 (Defra, 2006) has been released to reflect most recent findings such as land movement and the effects of thermo-expansion of the sea. The guidance provided new allowances for sea level rise which should be used to determine base cases and options to be compared to the base case. Indicative sensitivity ranges for peak flows, extreme rainfall, extreme waves and winds are given which should be used to test the base case and options to determine how a decision is affected by climate change impacts.

The Defra estimates of global mean sea level up to 2080 are based on the IPCC Third Assessment Report (TAR) (2001) *High emissions scenario (A1FI)*. Post 2080 projections are based on an extrapolation of the 2020s, 2050s and 2080s global mean sea level estimates. The respective IPCC TAR global average sea level rise range, for the 2050s and 2080s respectively is, 9-36cm and 16-69cm.

These precautionary Defra allowances for global mean sea level rise were reviewed in May 2007 in the light of the IPCC 4th Assessment Report and were found to still be reasonable.

7.2.3. Net sea level rise

The estimations of future net sea level change are based on two components: isostatic changes, which refer to adjustments in the absolute elevation of the land; and eustatic changes, which refer to variations in the absolute elevation of the sea surface caused by variations in the volume of the oceans. Together they are used to estimate net sea-level change, taking into account changes in both land and sea surface level (UKCIP, 2007). On top of this, changes in storm surge in the future must be factored in.

Isostatic subsidence

Ireland is undergoing isostatic subsidence in its recovery from the ice age. At present there is little information on land movement in the Irish context. However, work in Dublin (Greater Dublin Strategic Drainage Study, 2005) includes estimates of land movement of -0.3mm/yr for the Dublin area.

A more recent study shows different results suggesting that the Fingal and East Meath area is undergoing uplift with values interpreted from the map of around +0.3mm/year (Figure 7-1).

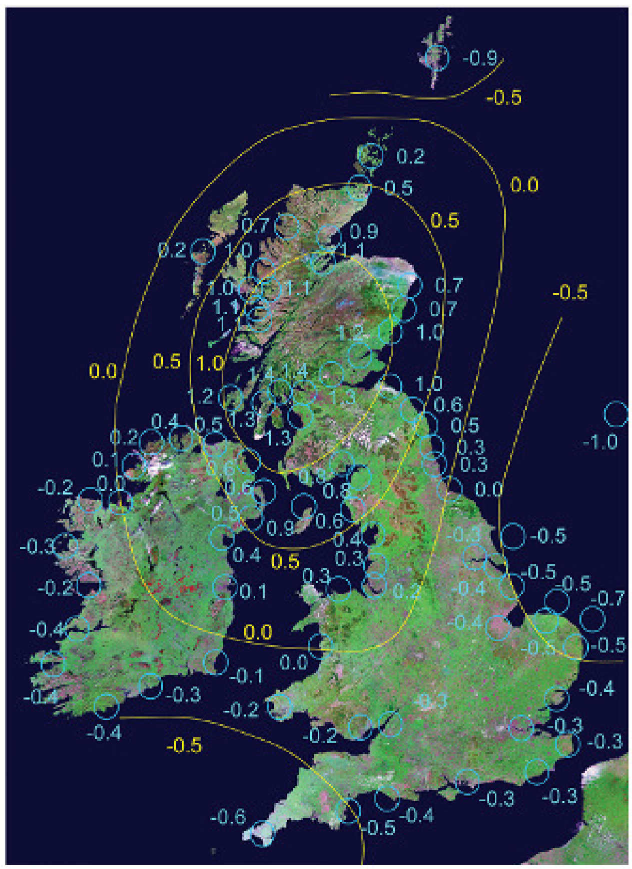

Figure 7-1: Current rate of relative land- and sea- level change in British Isles. Relative land uplift shown as positive in yellow in mm/year. Figure is taken from Shennan et al., 2009.

Table 7-1 summarises the land movement estimates applicable to the FEM FRAMS from these literature sources.

Table 7-1: Land movement (mm) estimates applicable for the FEM FRAMS from literature sources

Source	Land movement (mm/yr)
Dublin Drainage Strategy (2005)	-0.3
Shennan et al. (2009)	+0.3

** Negative represents subsidence*

Eustatic changes

Global and Ireland-specific estimates of change in sea level are available from climate change literature. However, much uncertainty exists not only in the modelling but in the scientific understanding of processes. Furthermore, global sea level change estimates will not apply equally to all parts of the ocean as warming and therefore expansion of water is not uniform. The UKCIP02 science report states that local values could be anywhere within ± 50% of the global average. Table 7-2 shows the range of predicted increases in sea level for three different future time horizons.

Storm surge

Storm surges are temporary increases in sea level, above the level of the astronomical tide, caused by low atmospheric pressure (depressions) and strong winds. They occur in shallow water regions, such as on the continental shelf around the UK and can result in local rises in sea level which can be very significant for flood risk, particularly if they coincide with high spring tides. Projected increases in the 50 year return period storm surge height are reported in the UKCIP02 report. Although the UKCIP project does not consider Ireland specifically, visual inspection of the storm surge maps (See Figure D-4 in Appendix D) provide some approximate values for three emissions scenarios. The values reported include sea level rise from eustatic changes (mean sea level rise due to thermal expansion of the oceans), isostatic changes (from vertical land movement) and changes in surge height (from increased storminess).

Table 7-2: Sea level rise (cm) estimates applicable for the FEM FRAMS from various Irish and UK literature sources for three future time horizons

Source	Net Sea Level Rise (cm)			Details
	2050	2080	2100	
IPCC (scenario A2)*			23 - 51	Global average sea level rise **Eustatic rise only** (against 1990 levels
IPCC (scenario A1F1)			26 - 59	Global average sea level rise **Eustatic rise only** (against 1990 levels
UKCIP02 (Medium-High scenario)	15	30		Global average sea level rise **Eustatic rise only** (against 1990 levels
UKCIP02 (High scenario)	18	36		Global average sea level rise **Eustatic rise only** (against 1990 levels
Sweeney *et al* (2003)			49	Global average sea level rise **Eustatic rise only** (against 1990 levels
Rahmstorf (2007)			55 -125	Best estimate of sea level rise based on range of scenarios- no storm surge
Defra FCDPAG3 (2006)	33	65	93	Guidance policy [SW England and Wales]
IPCC A1F1 eustatic estimates with 0.3mm subsidence**			16 - 92	Global average eustatic sea level rise ± 50% + 110 years of 0.3mm/yr subsidence
UKCIP02 (High scenario) with 0.3mm subsidence**	11 - 29	21 - 57		Global average eustatic sea level rise ±50% + 110 years of 0.3mm/yr subsidence
IPCC A1F1 eustatic estimates with 0.3mm uplift**			10 – 85	Global average eustatic sea level rise ± 50% + 110 years of 0.3mm/yr uplift
UKCIP02 (High scenario) with 0.3mm uplift**	6 - 24	15 - 51		Global average eustatic sea level rise ±50% + 110 years of 0.3mm/yr uplift
UKCIP02 Science Report		~20		Low emissions scenario- including eustatic, isostatic and surge effects
UKCIP02 Science Report		~40		Medium emissions scenario- including eustatic, isostatic and surge effects
UKCIP02 Science Report		~70-80		High emissions scenario- including eustatic, isostatic and surge effects

** A2 equivalent to Medium-High UKCIP02 scenario;*

***For information on estimates of land movement see Table 7-1.*

7.2.4. Increase in precipitation and flow

Global and Ireland-specific estimates of future increase in precipitation are available from climate change literature. Table 7-3 shows the range of predicted increases in precipitation for three different future time horizons. However, it is noted repeatedly that little change is expected on the east side of Ireland where the study area lies.

Table 7-3: Estimates of increase in precipitation or river flow (%) applicable to the FEM FRAMS from various UK and Irish sources for three future time horizons

Source	2050	2060	2080	2100	Change Parameter	Detail
UKCIP02 (Medium-High scenario)	10%		15%		Rainfall	Increase in winter precipitation
UKCIP02 (High scenario)	10%		15%		Rainfall	Increase in winter precipitation
UKCIP02 (High scenario)			20-25%		Rainfall	Increase in scale of the 2-year return period event.
Sweeney and Fealy (2006)			11%-17%		Rainfall	Increase in winter precipitation
McGrath *et al* (2005)		10%			Rainfall	Increase in December precipitation
Sweeney, *et al* (2003)	11%				Rainfall	Increase in winter precipitation
Defra FCDPAG3 (2006)*	10%	20%	20%	30%	Rainfall	Peak rainfall intensity (preferably for small catchments)
McGrath and Lynch (2008)	<20%				River Flow	Increase in mean daily winter flow
Defra FCDPAG3 (2006)*	20%	20%	20%	20%	River Flow	Peak river flow, for large catchments] see

** The values included represent sensitivity range to be adopted for peak river flow*

7.2.5. Conclusion – climate change

- All climate change projections are highly uncertain, with the sources of uncertainty coming from climate modelling, emissions uncertainty and natural variability.
- The literature review has shown that a variety of predictions exist for future sea level rise and increase in precipitation that could be incorporated into the Fingal and East Meath FRAMS, for future time horizons.
- The various predictions require consideration and a decision on which is to be adopted as part of the Fingal and East Meath FRAMS. It may be that the 2050 year horizon is adopted in design, with the provision for adaptability of flood relief works in the future to account for either the 2080 or 2100 climate change scenario.
- Land movement should be considered as part of any sea level rise estimate adopted,

however, changes in sea level due to land movement are far exceeded by changes due to thermal expansion and storm surge. Estimates of the current rate of relative land-level changes are conflicting for the FEMFRAMS area with both positive and negative land movement estimates. The overall impact these values have on the sea level change estimates is, however, of little consequence.

- A key factor in the decision-making process is ensuring that flood relief options adopted today allow for adaptability in the future, so that when further climate change estimates are available these can be incorporated.
- The UKCP09 climate change scenarios - the first report on results from the UKCP09 study was published in June 2009. These scenarios will provide probabilistic climate change projections for the first time which will help in quantifying flood risk in Fingal East Meath.
- There are some suggestions that current emissions are tracking slightly above predicted emission ranges, exceeding the High emission scenarios used previously. This may mean that projections of future change in sea level and rainfall may under-estimate actual changes.

7.2.6. Recommendations – climate change

Based on the above discussions, Table 7-4 contains recommended ranges of change in sea level and peak river flow for adoption in the Fingal East Meath study area for two future scenarios; mid range future scenario (MRFS) and the high end future scenario (HEFS). Both scenarios are applied over a 100 year time horizon. The MRFS adopts the mid range of future predictions from the literature review while the HEFS adopts the higher end of predictions to allow for an assessment of potential flood defences against a more extreme change in climate.

Table 7-4: Climate change recommendations for FEM FRAMS over a 100 year time horizon

Recommended change in net sea level and rainfall due to climate change for the Fingal East Meath catchments			
Net sea level rise (cm) (incorporating isostatic change, mean sea level rise and allowance for storm surge)		Increase in rainfall (%)	
MRFS	HEFS	MRFS	HEFS
35	100	20	30

The impact of these future environmental changes will be considered as part of the FEM FRAM Study, along with other future catchment land use changes described in the subsequent sections.

Increase in rainfall: these ranges have been selected based on the research findings reviewed and include an (uncertain) allowance for change in convective rainfall, based on the sensitivity allowances proposed by Defra (October 2006) for change in peak rainfall intensity.

Sea level rise: these ranges have been selected based on the research findings reviewed in this study.

7.3 Land use change

7.3.1. Introduction

The impact of land use change is an important consideration when assessing future flood risk in a catchment. Changes in agricultural practices, inclusion of sustainable urban drainage systems (SUDS), development of wetland habitats and other floodplain improvements, afforestation and urbanisation can all have an influence on flooding. This section focuses on the impact of afforestation and land use management on future flood risk. It also considers the development of future scenarios to be incorporated into the modelling of flood risk for the catchment. Urbanisation is a particularly important factor in the Fingal East Meath catchment and is looked at in detail in section 7.4. The impact of the incorporation of SUDS in future developments is discussed in section 7.4.6.

7.3.2. Afforestation

The Corine 2000 - Ireland Land Cover Update (2004) assessment shows that significant growth in forestry has occurred in Ireland between 1990 and 2000, growing from 10.2% to 11.9%. However, in the Fingal and East Meath catchment in 2000 there were around 130 hectares covered by forest cover. This represents less than 0.2% of the total catchment area. The forests in the Fingal and East Meath catchment are composed of broad-leaf forest, and are mainly located in the northern part of the catchment.

In the upland areas where forestry is increasingly concentrated, land is usually poorly drained and peaty, so that the soils often require artificial drainage. Pre-afforestation land drainage generally involves the removal of surface water, the drying of the soil and the suppression of vegetation on the overturned turf ridges and in the excavated ditches. The drainage causes an immediate increase in both high and low flows: flood flows tend to be “peakier”, with shorter response times and higher peaks, whilst base flows generally increase. In the 10-year period following drainage and planting, there is a tendency for the response times, peak flows and base flows to begin to regress towards their pre-drainage values. This is a result of the decay of the drainage ditches and infilling with vegetation, in addition to the increasing consumption of water by the growing tree crop. The overall effect of mature forests on flows is still the subject of debate. The steady growth of trees on drained land appears to result in a steady reduction in peak flows, caused largely by a reduction in runoff volumes. It is likely that base flow will also eventually be reduced as the forest matures further (Flood Estimation Handbook, 1999).

Planting trends from 1999-2006 show that planting in County Dublin (including Fingal) have dropped to zero (See Figure 7-2). Although planting rates in County Meath are higher, this still only amounts to a small proportion of the country area: forest cover in 2006 was 3.93% for County Dublin and 2.87% for County Meath (Statistics 2006 - Afforestation, Forest Service). Furthermore, as planting is a decision for private landowners and as a result of competing land uses and environmental restrictions (Factors Affecting Afforestation in Ireland in Recent Years, Malone, 2008), afforestation in the Fingal and East Meath catchment is not likely to be significant in future.

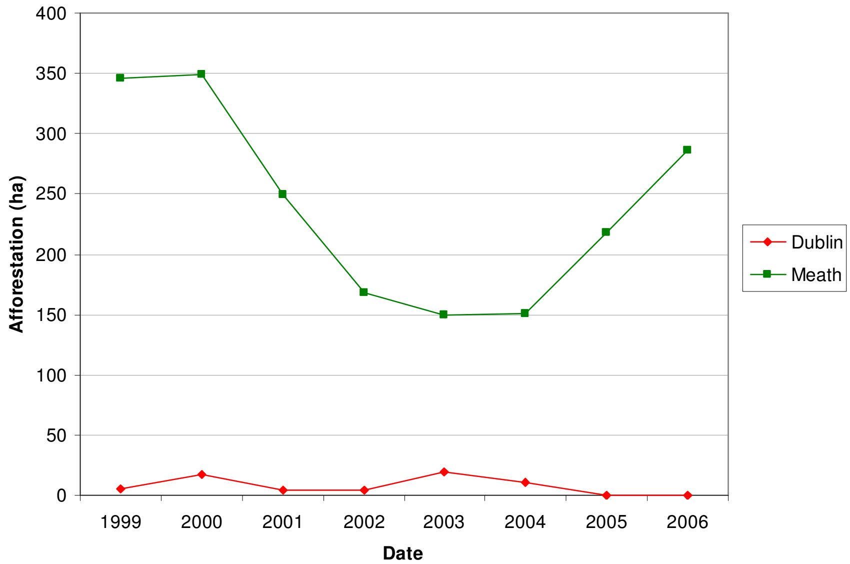

Figure 7-2: Recent trends in afforestation in County Dublin and County Meath

7.3.3. Impact of land management on hydrological processes

The impact of change in land use on flood generation is difficult to predict. A range of field trials have been undertaken, producing a variety of results. The evidence base for Coalburn, Plynlimon and Balqhuhidder study sites strongly suggests that upland conifer forests have a negligible effect on reducing peak flows for large events. This is in part as a result of the effects of the different parts of the cropping cycle cancelling each other out. In their general review of the history of forest hydrology, McCulloch and Robinson (1993) conclude that forests should reduce flood peaks, except for the effects of drainage and forest roads. A review of results from 28 monitoring sites throughout Europe (Robinson et al., 2003) concluded that the potential for forests to reduce peak flows is much less than has often been widely claimed, and that forestry appears to "... probably have a relatively small role to play in managing regional or large-scale flood risk". Furthermore, a study at Pontbren shows that the most extreme floods tend to occur when the ground is fully saturated and in this case the effect of interception losses by the canopy or increased infiltration rates in the soil are irrelevant.

In summary, there is quantifiable evidence that both afforestation and field drainage can affect flows in the surface water network but the impacts can be very different, depending on the local soil type and specific management practices used.

7.4 Urbanisation

7.4.1. Introduction

The National Development Plan (NDP) 2007-2013 identified the Dublin gateway as key for investment so that it can compete at international level and act as a driver for national development. Population growth and housing development, driven by the Dublin economy, is occurring well beyond the boundaries of Dublin. Part of the catchment (towns such as Swords and Malahide) falls within the metropolitan area.

Strategic planning guidelines for the Greater Dublin Area (GDA) are already in place. The National Spatial Strategy (NSS) envisages the continued development of the GDA but in a more compact and sustainable manner, anchored through higher density development around a strengthened public transport grid.

7.4.2. Ireland urban cover to date

The *Corine 2000 - Ireland Land Cover Update (2004)* assessment (Figures 7-3 and 7-4) shows that significant increase in the area of land covered by artificial surfaces has occurred in Ireland between 1990 and 2000, growing from 1.5% to 1.9%. All of these increases are probably related to the economic growth in Ireland in the 1990's and the demand for new housing. There was also an extensive building of new infrastructure (e.g. motorways) during this period. Urban development and associated infrastructure covers approximately 35 sq km in the Fingal and East Meath catchment, which is approximately 4.6% of the total area. Development is principally concentrated around the coast in towns such as Swords, Malahide and Portmarnock in the south and Rush, Skerries and Balbriggan further north (Figure 7-5).

7.4.3. Urban development effects on flood risk

It is generally accepted that urban development increases runoff because of the greater impermeability of urban surfaces, which has a marked effect on the flood behaviour of a catchment. Typically it accelerates and intensifies the flood response (*Flood Estimation Handbook, 1999*).

7.4.4. Fingal and East Meath development

Population growth

The strategic planning guidelines from 1999 estimate future population growth - number of household could increase by 48% and employment by 40%. However, recent regional population projections (for the period 2011 to 2026), released in December 2008 by the Central Statistics Office, show that under certain scenarios the population in Dublin will actually decline as a result of lowered in-migration and a recent trend of people moving away from the capital. Even without in-migration, population growth in Dublin is predicted to be 0.7% annually over the period. However, the population of the mid-east is set to increase substantially under all scenarios (increase of between 39-73% between 2011 and 2026). Projections from 1999 for a 15 year period showed a growth of 38-48% in household demand.

County, Regional and Strategic development plans

The strategic planning guidelines identify Balbriggan as a Primary Development Centre. The National Spatial Strategy states that Primary Development Centres need to aim at a population level that supports self sustaining growth, but which does not undermine the promotion of critical mass in other regions. This suggests an ultimate population horizon of up to 40,000 people for the primary development centres.

However, much of the rest of the catchment is a strategic ‘green-belt’ area for Dublin and development in smaller towns and villages will be restricted. Current development plans describe future development in the Greater Dublin Area as more compact and sustainable, anchored through higher density development.

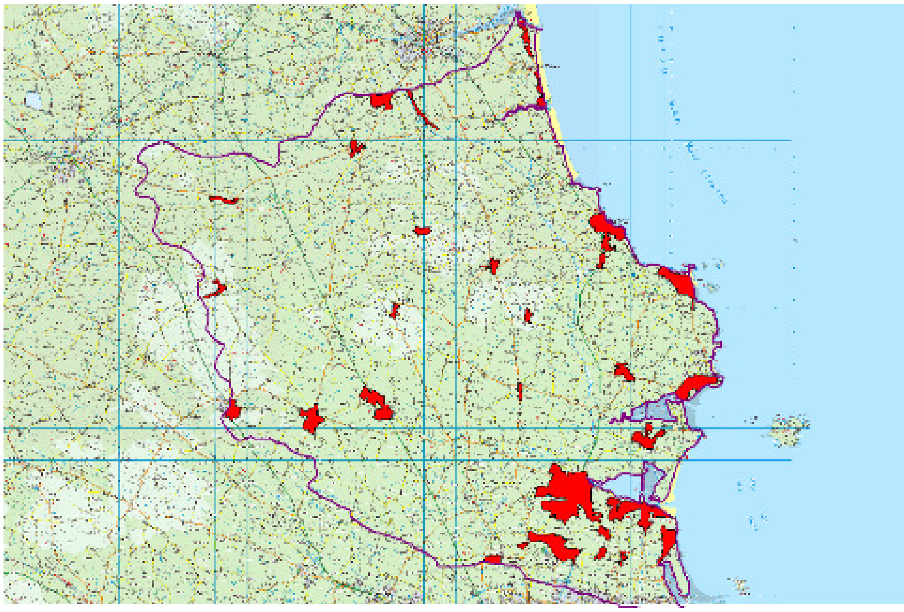

Figure 7-3: Urban land cover from the Corine land cover dataset of 2000.

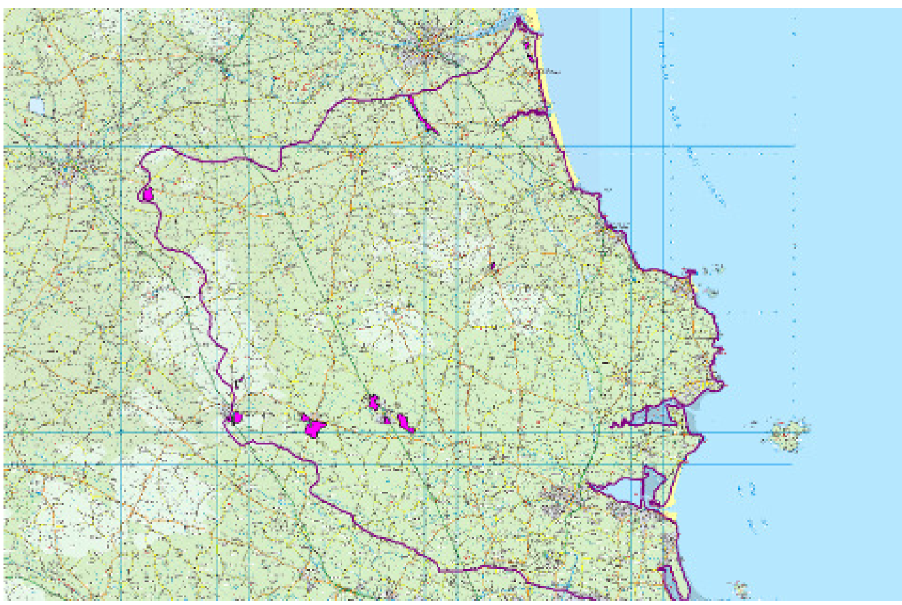

Figure 7-4: Change in urban land cover between 1990 and 2000 as described by the Corine land cover dataset (2000)

Strategic plans identify Balbriggan and Swords as areas for expansion. Balbriggan has been growing rapidly and population currently stands at around 17-18,000, but plans are to grow it to 40,000. This depends largely on whether the plans for a port go ahead. The vision for Swords is to grow it from its current 40,000 population into a self sustaining town of around 100,000.

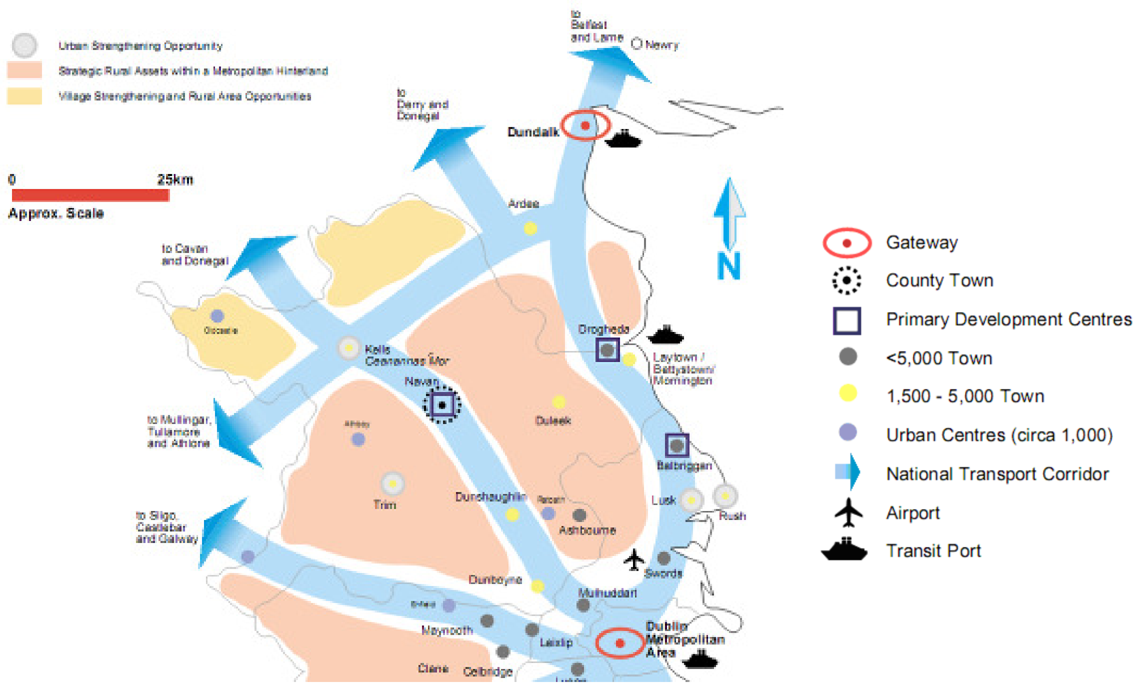

Figure 7-5: Strategic planning guidelines from the National Spatial Strategy showing the area around the Fingal and East Meath study area

7.4.5. Identification of urban future scenarios for FEM FRAMS

The impact of urbanisation on flood generation in a catchment depends on the spatial distribution of the urban cover. County Development Plans only look forward to 2011 and do not detail the extent of building but rather the strategy for each area.

There is great uncertainty in the extent of future development as the extent of building will depend on many factors such as the economic environment.

Policy guidance as provided by the Environment Agency for England and Wales, Catchment Flood Management Plan (CFMP) future scenario guidance (2006), states that in view of the relatively small impact on flood flows of development scenarios as compared to climate change scenarios, the level of analysis recommended is relatively broad-brush. It recommends that a 10% increase (over a 50-100 year period) in urbanisation should be used if no information is available. However, discussions with planners suggest this area could be under substantial pressure to develop in the future.

A possible scenario described by a Senior Planner at Fingal County Council would see most of the rural land between Dublin and Swords becoming developed, Balbriggan expanding towards the west and development pressures causing the towns of Lusk and Rush to join. It is unlikely that any of the smaller villages will expand greatly. For East Meath, planners have suggested that the greatest risk would be expansion of Drogheda South. Duleek may also extend back towards the M1 and Drogheda. Again, it is unlikely that the villages and heritage towns will expand greatly. By roughly marking these areas on a map they may amount to around 40 sq km of urban growth. This would represent a doubling in urban cover from 2000 (urban cover in 2000 was 4.6%).

Discussions with Michael Grace of Brady Shipman Martin planning consultants highlighted that development is likely to occur along the Dublin Belfast corridor and further confirmed that a doubling in urban cover could occur up to 2050, and that a further doubling could occur between 2050 and 2100.

Most of this development is in the very lowest parts of catchment by the coast which has a lesser effect on increased flood peaks as the increased speed of runoff from this area should cause a greater de-synchronisation between the runoff from this area and those areas up-stream. However, the volume of runoff would also be increased.

To assess the urban development it is necessary to apply an adaptation to the hydrological parameters. Based on the review of the development plans and information received from Local Authority planners and planning consultants, suggested increases in urban cover for the MRFS and HEFS are outlined in Table 7-5.

Table 7-5: Future urban development scenarios – hydrology parameters

Recommended ranges of future urbanisation for the Fingal and East Meath catchments (Increase in urban area)	
MRFS	**HEFS**
100%	400%

7.4.6. Policy to aid flood reduction

The drainage of any development, whatever size or location, should consider the opportunity to use appropriate Sustainable Urban Drainage Systems (SUDS). Adoption of SUDS is to minimise the post-development runoff to pre-development conditions. SUDS facilitate attenuation and treatment of surface water and may include one or more of the following: permeable surfacing, infiltration/filter trenches, filter strips, soakaways, swales, detention basins, constructed wetlands and ponds.

If SUDS were to be incorporated into all planned development within the Fingal and East Meath catchments and maintained adequately then this would negate the adverse impact of the development on the runoff. Based on this assumption, the post-development condition would be equal to the pre-development condition. The incorporation of SUDS into all types of development is mandatory under the requirements of the Greater Dublin Strategic Drainage Study – Volume 2 New Development. Section 4.2 of this document states that “SUDS is therefore mandatory for all new developments, except where the developer can demonstrate that its inclusion is impractical due to site circumstances.”

However, policy guidance on SUDS may not specify up-take by all types of development; therefore it is difficult at this stage to account for which percentage of future development would apply SUDS. It should be noted that SUDS are normally designed for a specified frequency of event e.g. the 3% Annual Exceedence Probability (AEP) event. Therefore it could be assumed that when flood producing events with low AEP occur e.g. 0.5% AEP, even developments with SUDS will not be able to attenuate the runoff.

7.4.7. Conclusions - urbanisation

- Urban development can increase and intensify runoff.

- Two future scenarios have been suggested to reflect the hydrological effects of urban development on the Fingal and East Meath study area, to be applied to the lower reaches of the Fingal and East Meath catchments.
- Adoption of SUDS can aid in reducing runoff to pre-development conditions.

7.5 Combination effect of future drivers of flood risk

The dominant factors influencing future flood risk in the Fingal and East Meath catchments include changes in climate, land use and urban growth. The effects of these three factors are described in Section 7.2, 7.3 and 7.4, respectively. As little afforestation is likely to occur in the FEM FRAMS study area, the main factors for future flood risks can be considered as climate change and urbanisation. Table 7-6 collates both these projections (climate change and urbanisation) for the two future scenarios, namely, the mid range future scenario and the high end future scenario.

Table 7-6: Relevant combinations of drivers to provide boundaries for future flood risk

Driver	**Scenario**	
	MRFS	**HEFS**
Climate change - rainfall	+ 20%	+30%
Climate change - net sea level rise	+35cm	+100cm
Land use change – urbanisation	100% increase in urban area	400% increase in urban area

The above combinations of drivers for future flood risk will be applied during the hydraulic model runs for future scenarios. To incorporate future changes in urbanisation into the modelling, the changes in 'Urban fraction' will be applied to the relevant sub-catchments in the ISIS FSSR 16 boundary units. Similarly, the percentage increase in rainfall will also be applied to the ISIS FSSR16 boundary units. The change in sea level rise will be applied to the tidal boundary. This will then translate into the estimation of flows at each sub-catchment and hence into the modelling for the MRFS and HEFS scenarios, which will automatically generate inflows at the sub-catchment levels for these future scenarios.

8. Joint probability analysis

8.1 Background

A detailed research and analysis of the joint probability methodology (JPM) to be adopted for the hydraulic modelling in the FEM FRAM Study was carried out during the preliminary hydrology analysis. The analysis was based on the approach of the UK Defra/EA (2006), which was also used in the Lee CFRAM pilot study. The results of the joint probability analysis are presented in Chapter 7 of the Preliminary Hydrology Report. Further to the outputs from the Lee CFRAM pilot study, a Technical Note (TN) was issued to the client in November 2009 which reviewed the joint probability approach of the preliminary hydrology analysis and made some recommendations for the FEM FRAM Study. This chapter presents a summary of the joint probability methodology of the preliminary hydrology analysis as well as the updates and recommendations of the Technical Note on JPM.

8.2 Joint probability methodology - Preliminary Hydrology Report

8.2.1. Joint probability analysis - application to flood risk management

Joint probability, in terms of flood risk, refers to the chance of two or more conditions occurring at the same time to produce a high water level e.g. a combination of high river flow and high tidal level. High water levels are often caused by more than one environmental variable, so that the probability of a certain level of occurring is related to the combined probability of occurrence of all the variables concerned. There is often a degree of dependence between the variables, and an assessment of this dependence is required to evaluate the flood risk due to extreme events.

Joint probability analysis is often undertaken by generating a long-term simulation of hundreds of years of records of related variables whose distributions, dependences and extremes are known, for example by using Monte Carlo simulation. The analysis is usually undertaken as a stand alone project with specialist software. The analysis requires the collection of high quality concurrent data, processing, and statistical analysis.

In the UK, Defra/EA has been funding research into JPMs for use in flood risk studies for many years. The most recent study: Joint Probability – Dependence Mapping and Best Practice [FD2308] (2006) has provided the latest joint probability best practice and dependence mapping for Great Britain. The report details dependence between a range of variables, particularly relevant to the FEM FRAM study is the assessment of dependence between river flow and surge.

Detailed dependence mapping of variables is not available for Ireland. In addition, the quality and length of flow data and tidal records is not sufficient to provide detailed correlation between them. Therefore the assessment made for the joint probability design scenarios is based on the best available information on dependence from the Defra/EA study. The Defra/EA study estimates dependence between river flow and surge, but it is noted that it is not inappropriate to assume that the same level of dependence also applies to river flow and sea level. This assumption has also been used within the FEM FRAM study. The method adopted is the ‘desk study approach’, extending on a method originally published by CIRIA (1996). The purpose of the method is to construct tables of joint exceedence extremes, using existing information on single variable extremes and an estimate of the dependence between the two variables required.

8.2.2. Dependency assessment

The UK Defra/EA 2006 study

The joint probability methodology requires an assessment of dependence (χ) between river flow and surge. The Defra/EA study found that χ >0.1 has high dependence, for example in the Firth of Forth in Scotland and along the west coast of England. Lower dependence, χ <0.1, has been found on the east coast of England.

The degree of dependence between surge and river flow depends not only on the nature of the surge locally but also on the catchment response to rainfall. The Defra/EA study noted that the east coast of England had high dependency between surge and rainfall but low dependency between surge and river flow. Highest dependency was found where the catchment responded quickly to rainfall and where the surge was prolonged (which lengthens the window within which high levels can occur concurrently).

Climate change impacts were also addressed within the dependence mapping for the Defra/EA study (FD2308/TR1), as climate change may affect the dependence between individual source variables e.g. due to changes in storms, etc. Although there is much uncertainty associated with the actual values of dependency produced by the model, the change in dependency associated with climate change is more reliable.

Dependency values between river flows in Wales and Northwest England and the Holyhead surge station (on the Irish Sea) vary between -0.01 and 0.16 (are significant at the 5% level. The maximum of the upper bounds of the 90% confidence interval is for the River Dee in North Wales with a value of 0.24.

Fingal and East Meath dependency

In the absence of a full joint probability analysis e.g. with Monte Carlo simulation, a pragmatic approach is required within the FEM FRAMS to ensure that a conservative estimate of dependence is used. For the study catchment, it can be assumed that the level of dependency would be relatively low as a result of the relatively permeable east facing catchments and also because surges in the Irish Sea, though intense, tend to form and dissipate rapidly within a single 12 hour tidal cycle (TR3 Defra, 2006).

With regard to the information provided by Defra/ Environment Agency in the Joint Probability Reports (FD2308) and with respect to the geographic and hydrographic character of the Fingal and East Meath catchments, a conservative estimate of dependence of χ = 0.2 is considered appropriate. This is relatively high dependency but corresponds with some of the rivers in Scotland and England with high correlation between tidal levels and fluvial flows and also allows for a potential increase in dependency as a result of climate change.

A review of the historical flood data reveals that two recent events (November 2000 and 2004) were considered to be both fluvially and tidally influenced (refer to Table 3-2). This provides some evidence of dependence and therefore, supports the adoption of the conservative value of χ = 0.2. A detailed Monte Carlo assessment of the fluvial and tidal flow records is beyond the scope of this study.

8.2.3. Design combinations of flow and sea level

Based on a high dependence of χ = 0.2, the design scenario curves for a range of return periods were produced. Figure 8-1 shows the resulting joint exceedence curves. A curve represents all combinations of flows and tidal levels which could potentially cause maximum water levels in the river for the chosen return period. Based on the curves two design scenarios are proposed for each return period, as shown in Table 8-1.

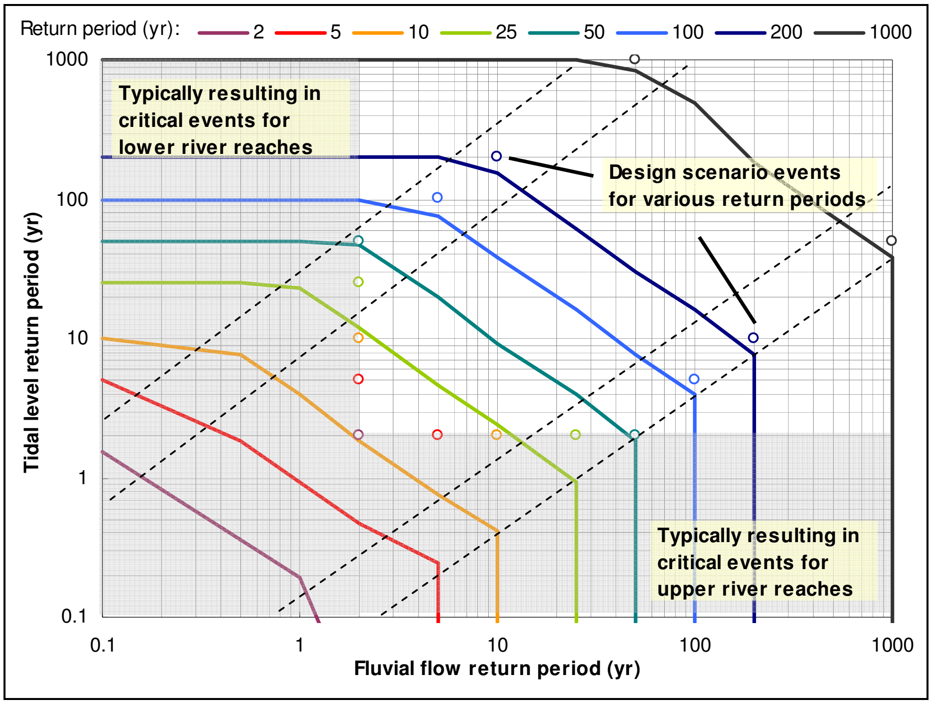

Figure 8-1: Joint exceedence curves for various return periods

Table 8-1: Combinations of individual return periods necessary to produce design event

Design event	Boundary return period	
	Fluvial boundary	Sea level boundary
2 year	2	2
2 year	2	2
5 year	5	2
5 year	2	5
10 year	10	2
10 year	2	10
25 year	25	2
25 year	2	25
50 year	50	2
50 year	2	50
100 year	100	5
100 year	5	100
200 year	200	10
200 year	10	200
1000 year	1000	50
1000 year	50	1000

For each respective return period curve, the joint probability analysis has been simplified to two scenarios (represented on Figure 8-1 by coloured points relating to the respective return period). For example for the 100 year return period, the curve has been simplified to the 100 year tidal level with 5 year flow, and 100 year flow with 5 year tidal level. These two scenarios lie just outside the extremities of the curve, and are therefore conservative.

8.3 Update of the preliminary hydrology joint probability approach

8.3.1. Review of the GDSDS approach

Subsequent to the issue of the Preliminary Hydrology Report and specifically further to the outputs from the Lee CFRAM Study, it has been hypothesised that the proposed approach may result in a conservative/cautious estimation of flooding with respect to the joint probability.

In this regard, Halcrow Barry reviewed Volume 5 of the Greater Dublin Strategic Drainage Study (GDSDS, 2005), which is about policy on climate change and the approach to joint probability. The GDSDS suggests that '*a pragmatic and conservative set of assumptions needs to be applied*' to joint probability analysis. The study recommends the following event combinations are adopted for the 100-year probability/combined probability.

- MHWS with 100 year river
- 1 year tide with 5 year river
- 5 year tide with 1 year river

With the exception of the MHWS with the 100 year river flow combination, the view of Halcrow Barry is that adoption of the GDSDS approach for combined probability could lead to an underestimation of flooding.

8.3.2. Review of the preliminary hydrology joint probability approach

The Halcrow Barry proposal in the preliminary hydrological analysis indicated that the joint probability approach would be based upon best practice approaches that were developed for Ireland and which were to be applied to the Lee CFRAM pilot study. This was based on an EA/Defra study: Joint probability – Dependence Mapping and Best Practice [FD2308] (2006).

The main assumptions in the method applied to Lee CFRAMS and FEM FRAMS are:

1. The dependency between flows and surge is the same as the dependency between tide and sea level
2. The response of the tidal river system can be represented by two [flow, sea level] scenarios
3. The dependency parameter is χ=0.2
4. Low magnitude events (with return periods less than two years) can be approximated by the 2 year return period

The effects of these assumptions are assessed below. Throughout the text, conservative implies the method used will over-estimate flood risk.

Assumption 1: Dependency between flows and surge are used here as a proxy for the quantity of interest, the dependency between flow and sea level.

To illustrate the difference, consider an estuary system such as the Severn and Bristol Channel. There is a well-known negative dependency between surge and tide in the Severn.

Any positive dependency between flow and surge would therefore indicate a negative dependency between flow and tide level, despite χ>0.

The magnitude of such interactions is estimated in FD2308/TR1, and shown in Figure 8-2 below taken from that report. FD2308 recommends that for regions of no/low interaction, the surge can be considered independent of tide. The figure indicates that interactions are insignificant for St Georges channel and there is medium interaction in the Irish Sea. The interaction around the South East coast of Ireland is likely to be somewhere between these two, which may mean interaction between tide surge interacts to reduce the sea level for a given return period. The assumption that there is no interaction in the FEM FRAMS case is therefore **conservative**.

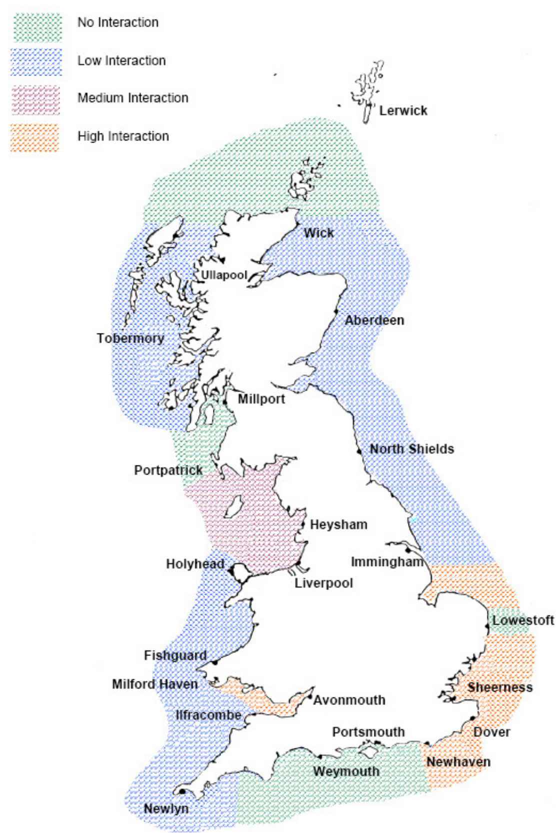

Figure 8-2: Interaction between surge and tide (source: FD2308/TR1)

A related issue is the use of daily maximum surge levels to estimate χ in FD2308. The daily surge maxima may not coincide with high astronomical tides (unlike measurements based on peak tide/surge measurements), and therefore some adjustment is required. FD2308 recommends a factor of 1.37 to adjust from χ estimated from daily maximum surge measurements to dependency for peak tide/surge levels, which increases the joint return period for a given set of marginal return periods. No adjustment is made in the FEM FRAMS method. Hence the return periods presented in the Table 8-1 above are too low, and the water levels at these return periods actually correspond to longer return periods. The FEM FRAMS method is therefore **conservative**.

Assumption 2: There may be some part of the models that respond to different combinations of sea level and flow from the ones listed in the Table 8-1 above. The effects of this will be exacerbated by non-linear floodplain response to river water levels, e.g. caused by defences.

Interactions such as these tend to be associated with long, complex estuaries with long reaches where risk from tidal and fluvial events is of similar magnitude (e.g. Thames, UK). Estuaries in the FEM FRAMS area are likely to have relatively simple responses, so the regions where other scenarios generate maximum water levels are likely to be limited. The assumption is therefore **mildly non-conservative**.

Assumption 3: χ=0.2 is the highest value observed round the coast of England and Wales in FD2308, indicating "super dependent" variables. High dependency for England and Wales is mostly associated with quickly responding catchments with a southerly to westerly aspect, although geography means that there are no results for easterly facing catchments draining into the Irish Sea. Nevertheless, for the FEM FRAMS catchments we would expect the value χ=0.2 to be **conservative**.

Assumption 4: This assumption will only be important if inundation from short return period events generates significant flood risk. This assumption is **conservative.**

8.3.3. Recommendations

The combination of the conservative assumptions, along with a mildly non-conservative one, indicates the method used in FEM FRAMS to model dependency is conservative, and hence suitable for use in this level of study.

Therefore the combinations suggested in Table 8-1 (based on the JPA results published in the Preliminary Hydrology Report) were used for the hydraulic modelling to produce flood risk maps of various design AEPs.

9. Summary, conclusions and recommendations

9.1 Summary and conclusions

The hydrological assessment for the FEM FRAM study has been undertaken in two phases, namely, the preliminary hydrology analysis and the detailed hydrology analysis.

The preliminary hydrological analysis involved:

- detail review of historic floods in the study area,
- analysis of rainfall data to estimate design rainfall at the meteorological stations in the study area,
- analysis of the annual maximum flow series to estimate design floods at the hydrometric gauging stations and
- analysis of the joint probability methodology (JPM) to be adopted for the hydraulic modelling in the FEM FRAM Study.

The results of the preliminary hydrology analysis were reported in the Preliminary Hydrology Report, published in February 2009.

The detailed hydrology analysis reported in this study involved:

- review of the high flow ratings of the study area hydrometric stations,
- refinement of design floods at the hydrometric stations using statistical method and involving the reviewed annual maximum flood data,
- sub-dividing the study area rivers and streams catchments into 270 sub-catchment units and defining the methodology for generating design inflows at this sub-catchments using the FSSR 16 and IOH 124 UH method,
- assessment of future climate and land use changes in the study area and their effects on the flood regime of the study area,
- summary and updates (if any) of the rainfall analysis, review of historical floods and joint probability methodology of the preliminary hydrology analysis

In order to provide as accurate an assessment of extreme flows as possible using methodologies and data available, a detailed review of the rating curves was undertaken at nine hydrometric stations of the study area. The result of this review is to increase confidence in the out of bank flow estimates at these stations and thus increase confidence in the flow estimates.

This report identified that at Station 08009 Balheary on the Ward River, which is an A1 quality station as per Hydro-Logic Report (2006), the EPA provided hydrometric data and the reviewed rating produced annual maximum flows and specific Q_{med} much smaller than those of the other stations in the study area. Investigations into the reasons of the underestimated Q_{med} at this station are ongoing; it has therefore been decided not to include the annual maximum series data of this station for further analysis. Instead, a study area specific Q_{med} has been assigned for this station.

A study area growth curve has been derived using the FEH pooling group methodology, involving seven annual maximum series (AMS) from the study area and five from neighbouring catchments. The resulting study growth values are much higher than those of the FSR and also somewhat higher than those recommended by the GDSDS, which is in line with other similar research.

Due to the inherent uncertainty associated with hydrological estimates, confidence limits have been derived for the study area growth curve as well as for the return period flood estimates to reduce the uncertainty associated with the estimates. Methods proposed under the ongoing FSU for calculating standard error in the Irish AMS have been used for this purpose.

When the hydraulic models are run, the total (routed) flow in the hydraulic model at each gauging station, produced by all the upstream sub-catchments, will be reconciled with the design flow estimated from the statistical method, using iterative hydraulic model simulations.

To facilitate the assessment of potential future flood risk, two future flood risk management scenarios have been proposed; a Mid Range Future Scenario and a High End Future Scenario. The range of parameters incorporated in each of the future scenarios has been determined from a comprehensive review of current research.

9.2 Recommendations

At present, the study area has only two operational hydrometric gauging stations operated by the OPW. With the installation of data loggers at further two stations in November and December 2009, these have become operational. All other hydrometric stations in the study area operated by local authorities (assisted by the EPA) were closed during the period 1995-2001. The closed hydrometric stations therefore missed the opportunities of recording useful information on the recent significant flooding incidents in the study area. These information would have provided valuable information for the calibration of the hydraulic models and also for the future flood forecasting in the rivers and streams in the study area.

Therefore, a priority list of gauging station has been prepared for the phase-wise re-installation of these gauging stations. The recommendations are presented below:

- Continue the currently operational two gauging stations (Station 08008 Broadmeadow and Station 08011Duleek) and the recently re-installed further two stations (Station 08002 Naul (new) and Station 08010 Garristown) in the study area
- Immediate re-installation of Station 08012 Ballyboghill on the Ballyboghill River
- Re-installation of another thee stations, namely, Station 08005 Kinsaley Hall, Station 08009 Balheary and Station 08007Ashbourne with the first priority
- Re-installation of further four stations, namely, Station 08006 Hole in the Wall, Station 08003 Fieldstown, Station 08004 Owen's Bridge and Station 08014 Skerries with the second priority
- Identify new locations for the five stations, namely, Station 08003 Fieldstown, Station 08004 Owen's Bridge, Station 08005 Kinsaley Hall, Station 08009 Balheary and Station 08014 Skerries as the existing locations have either access or other difficulties.

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Glossary

A	Catchment area (km^2)
AAR	Annual Average Rainfall (mm)
Annual Exceedence Probability (AEP)	The probability that an event of a specified magnitude will be exceeded in any given year
Annual Maximum Series (AMS)	A series consisting of peak flow values which replaces the hydrograph of each year by its largest flood.
APSRs	Areas of potential significant risk
APMRs	Areas of potential moderate risk
Catchment	The total area of land that drains into a watercourse
CV	Coefficient of variation
DAFF	Department of Agriculture, Fisheries and Food (Ireland)
Defra	Department for Environment, Food and Rural Affairs (the UK)
EA	The Environmental Agency (the UK)
EPA	Environmental Protection Agency (Ireland)
F(i)	Gringorten plotting position value in terms of its i^{th} position
Flood Estimation Handbook (FEH)	Publication (1999) giving guidance on rainfall and river flood frequency estimation in the UK
Flood Studies Report (FSR)	Current industry standard for flood studies in Ireland
Floodplain	The land adjacent to a stream or river that experiences occasional or periodic flooding
Fluvial	Related to a river or a stream
FSU	The Irish Flood Studies Update being carried out by the OPW
FSU-DDF	The Depth-Duration-Frequency mapping of Ireland carried out jointly by the OPW and Met Eireann as part of the ongoing

	FSU
GDSDS	Greater Dublin Strategic Drainage Study
GEV	Generalised Extreme Value Distribution, consisting of EV1, EV2 and EV3 distributions
GL	Generalised Logistic Distribution
HA	Hydrometric Area
HPWs	High priority watercourses
Hydrograph	A plot of the discharge of water as a function of time.
ISIS	1-D computational hydraulic model developed by Halcrow and HR Wallingford
M5-2day	Five year return period, 2 day (fixed duration) duration rainfall (mm)
M5-1h	Five year return period, 1 hour (fixed duration) rainfall (mm)
M5-60	Five year return period, 60 minute (sliding duration) rainfall (mm)
MPWs	Medium priority watercourses
N	Number of years of record (or number of annual maxima)
Q_T	Peak flow value of *T* year return period (m^3/s)
Q_{med}	Medium value from an Annual Maximum Series (m^3/s)
Q_{bar}	Mean value of an AMS (also referred to as the mean annual flood) (m^3/s)
Return period (T)	The average time elapsing between successive occurrences of some hydrological event.
Rmed-2day	Median value from annual maxima series of 2 day rainfall
Rmed-1hr	Median value from annual maxima series of 1 hour rainfall
SAAR	Standard period average annual rainfall
Se	Standard error

Tp	Time to peak of a unit hydrograph
TR	Technical Report
UH	Unit hydrograph
X_T	Regional growth factor (given by Q_T / Q_{bar} in FSR & Q_T/Q_{med} in FEH)
y_T	Gumbel reduced variate value for T-year return period
yr	Year

Appendix A: Drawings

Appendix B: Meteorological, hydrometric and historic flood data

Table B-1: Meteorological data available for the study (selected stations are highlighted)

Station	Location	Easting	Northing	Rainfall data available	Type
532	Dublin Airport*	316900	243400	1941-2007	Synoptic
632	Lusk G.S.	321700	254300	1949-1985	Rainfall
1032	Duleek G.S.	304700	268200	1949-1991	Rainfall
1332	Malahide Castle	322200	245400	1965-2006	Rainfall
1532	Balbriggan (Kilsaugh)	320500	262200	1969-1988	Rainfall
1632	Bellewstown	309800	267200	1975-1983	Rainfall
2232	Garristown (Tobergregan)	307800	256500	1995-2000	Rainfall
2332	Bellewstown (Collierstown)	308400	267000	1997-2006	Rainfall
2432	Ratoath	302200	251400	1998-2006	Rainfall
2532	Dunshaughlin (Lagore)	298800	253500	1998-2006	Rainfall
3723	Casement Aerodrome	304100	229500	1954-2006	Climatological Station
931	Kells (Headfort)	276100	276900	1941-2006	Climatological Station
2931	Warrenstown	292100	253500	1952-2006	Climatological Station
2638	Ardee(Boharnamor)	294100	290200	1968-2006	Climatological Station

**Hourly rainfall data at Dublin Airport and daily rainfall data at other stations*

Table B-2-1: Hydrometric data available for the study (selected stations are highlighted)

Station	Data Provider	Station Name	River Name	Data Start	Data End	Data length, years	Catchment Area, km^2	Q_{med}, m^3/s	Specific Q_{med}, m^3/s	High flow rating (Hydro-Logic)	E	N	Reason for not including in the analysis
Hydrometric stations in the study area (HA 08)													
08002	EPA	Naul	Delvin	1977	2002	24	37.0	4.40	0.27	A1	313115	261136	Included
08003	EPA	Fieldstown	Broadmeadow	1976	1998	22	76.2	19.89	0.71	B	311780	250212	Flow values not checked by EPA (rating reviewed)
08004	EPA	Owen's Bridge	Ward	1976	1981	5					310405	245857	Several gaps in the data, high flow rating quality unknown
08005	EPA	Kinsaley Hall	Sluice	1977	2000	23	10.1	3.17	0.53	A2	322114	243105	Included
08006	EPA	Hole in the Wall	Mayne	1977	1987	10					322191	241431	Several gaps in the data, high flow rating quality unknown
08007	EPA	Ashbourne	Broadmeadow	1977	1996	21	34.0	8.16	0.54	B	305926	252256	Included
08008	OPW	Broadmeadow	Broadmeadow	1978	2007	28	110.0	21.06	0.56	A2	317453	248652	Included
08009	EPA	Balheary	Ward	1980	1995	15	62.0	4.97	0.21	A1	318579	248027	Included
08010	EPA	Garristown S.W.	Stream	1983	1996	13	1.1	0.62	0.56	C	307869	258933	Included
08011	OPW	Duleek	Nanny	1980	2007	28	181.0	48.38	0.88	B	305297	268519	Included
08012	EPA	Ballyboghill	Ballyboghill	1980	1998	17	22.1	6.83	0.63	B	315029	253649	Included
08014	EPA	Skerries	Mill Stream	1983	2001						324925	259585	Several gaps in the data, high flow rating quality unknown
08017	OPW	Duleek (u/s)	Nanny								305185	268453	Data not available
Hydrometric stations in the neighbouring catchment (HA 07)													
07002	OPW	Killyon	Deel	1953	2005	47	285.0	18.3	0.24	A2	268401	249139	Included
07003	OPW	Castlerickard	Blackwater (Enfield)							A1 & B	271626	248908	Only pre-1969 flow values available
07005	OPW	Trim	Boyne	1975	2006	31	1282.0	99.0	0.40	A1	280005	256953	Included
07006	OPW	Fyanstown	Moynalty	1986	2005	20	176.0	27.5	0.51	A2 & B	279051	275764	Included
07007	OPW	Boyne Aqueduct	Boyne							A1 & B	269207	245268	Only pre-1972 flow values available
07009	OPW	Navan weir	Boyne	1953	2006	52	1610.0	99.6	0.34	A1	287905	266761	Included
07010	OPW	Liscartan	Blackwater (Kells)	1953	2006	48	717.0	55.3	0.35	A1 & A2	284624	268941	Included
07012	OPW	Slane Castle	Boyne	1940	2006	67	2408.0	191.0	0.48	A1	294983	273962	Included
Hydrometric stations in the neighbouring catchment (HA 09)													
09001	OPW	Leixlip	Ryewater	1956	2006	50	215.0	35.5	0.57	A1	300516	236430	Included
09002	EPA	Lucan	Griffeen	1978	2000	23	35.0	5.4	0.35	A1	303227	235137	Included
09037	EPA	Botanic Gardens	Tolka								314735	237466	Short data length (N < 10 years)
09102	EPA	Cadbury's	Santry								319908	239611	Short data length (N < 10 years)

Key: OPW = Office of Public Works; EPA = Environmental Protection Agency

Table B-2-2: Annual maximum series (m^3/s) used in the statistical analysis

Water year	08002 Naul	08005 Kinsaley Hall	08007 Ashbourne	08008 Broadmeadow	08009 Balheary	08010 Garristown	08011 Duleek	08012 Ballyboghill	07002 Killyon	07005 Trim	07006 Fyanstown	07009 Navan Weir	07010 Liscartan	07012 Slane Castle	09001 Leixlip	09002 Lucan
1940														161		
1941														129		
1942														125		
1943														101		
1944														191		
1945														252		
1946														261		
1947														267		
1948														152		
1949														134		
1950														134		
1951														152		
1952														96.7		
1953									9.9			18.9	18.9	140		
1954									27.6			63.8	63.8	455		
1955									10.5			13	13	118		
1956									10.3			26.3	26.3	140	38.6	
1957									17.6			29.2	29.2	165	49.9	
1958									9.7			18.6	18.6	94	35.5	
1959									21.1			30.3	30.3	150	44.6	
1960									18.3			31.4	31.4	186	47.5	
1961									12.1			20.1	20.1	104	15.5	
1962									13.8			25	25	122	30.6	
1963									15.3			26.3	26.3	120	25.2	
1964									22.1			39.6	39.6	191	49.9	
1965									36.9			38.8	38.8	276	64.8	
1966									19.7			28.1	28.1	140	54.2	
1967									21.1			36.4	36.4	196	50.5	
1968									26			32.9	32.9	238	69.1	
1969									17.3			23.9	23.9	131	21.2	
1970									25.2			-		134	26.1	
1971									25.2			-		110	27.4	
1972									11.5			24.3	24.3	75.9	35	
1973												49.1	49.1	96.7	35.5	
1974												50	50	185	48.1	
1975										61		34.9	34.9	96.7	20.4	
1976										86		124	48.3	131	32.5	
1977	3.88	2.05	4.80							78		99.3	43.9	141	24.4	2.86
1978	14.47	6.73	12.92	31.29						130		271	72.1	345	62.4	6.47
1979	9.12	5.17	16.10	39.32			65.4		19.2	137		232	59.9	327		8.86
1980	4.40	1.77	9.34	15.39	5.21		50.1	9.87	16.2	119		167	63.4	251	32	2.21
1981	3.54	4.63	6.99		2.95		21.7	9.89	17.9	95		99.9	68	205	22.4	3.64
1982	6.38	3.17	6.88	25.76	1.36		50.7	15.09	22.3	120		152		300	38	8.68
1983	2.72	1.14	6.95	15.11	3.12	0.58	55.3	5.19	23.6	95		111		248	40.7	4.27
1984	5.38	1.90	9.79	21.70	5.10	0.73	42.2	5.59	25.9	125		145		294	38.6	4.62
1985	6.89	6.54	17.87	30.52	5.17	1.57	88.0	18.48	19.5	96		125		282	48.1	16.61
1986	2.86	2.85	5.49	21.70	3.74	0.44	37.4	4.87	16.7	84	15.7	97	55	194	35.5	11.01
1987	3.64	5.26	8.11	13.67	5.01	0.89	35.6	6.76	19.9	99	28.3	117	68.4	255	26.1	5.56
1988	2.83	0.80	5.01		2.83	0.28	15.3	3.09	10.3	51	25.2	52.5	59.3	120	9.39	1.26
1989	3.64	2.05	9.06	15.11	5.24	0.62	46.8	6.83	27.8	134	30.5	206	77.4	372	43.5	3.27
1990	3.75	2.00	10.85	19.18	2.26	0.61	30.9	11.67	15.8	93	30.6	114	73.1	227	29.7	4.28
1991	5.01	1.45	5.80	21.38	3.57	0.84	62.8	10.67	17.8	100	26.5	135	66.3	266	27.9	2.37
1992	6.48	9.88	10.77	30.52	15.00	1.39	65.4		25	138	27.9	204	68.4	364	60.7	22.49
1993	9.56	4.11	13.71	22.36	6.89	0.74	70.2	8.31	19.3	95	34	122	75.7	258	29.7	9.71
1994	4.40		8.16	22.03			51.8		27.3	130	30.5	205	80.1	361	48.1	5.12
1995	3.51	2.19	4.85	14.57	4.97	0.51	41.7	8.97	13	71	32.5	114	90.8	291	25.2	1.93
1996	4.08	3.95	4.50	13.08		0.48	26.6	1.46	13.1	71	23.4	80.7	59.8	161	16.1	5.43
1997	6.40	4.53		14.60				3.23	18.2	84	20.7	102	55.5	199	21.6	6.37
1998	2.64	4.86		25.06			64.8	5.23	16.7	106	24.2	173	73.1	303	30.1	5.74
1999	12.61	1.57		9.28			18.2		18.2		20.1	120	60.8	222	24.4	
2000		11.40		32.06			85.1		25.2	127	31.9	256	89.1	425	81.8	23.75
2001				16.80			49.0		28.6	114	27.1	62.8	62.8	276	42.4	
2002	9.83		31.79	43.67			72.1		28.6	136	30.3	298	79	382	91.5	
2003				9.28			32.0		13	96.4	16.1	133	50.4	189	27.9	
2004				20.74			63.3		26.9	126	32.4	225	76.3	336	58.1	
2005				12.20			24.6		12.8	80.2	21.3	102	57.9	135	22.4	
2006				12.78			47.8			119		169	77.9	207	38.6	
2007				26.26			26.9									
Q_{med}	**4.4**	**3.17**	**8.16**	**21.0611**	**4.97**	**0.62**	**48.3832**	**6.83**	**18.3**	**99.0**	**27.5**	**99.6**	**55.3**	**191.0**	**35.5**	**5.43**

Table B-3-1: List of historic fluvial flooding events in the study area

Flood ID	Place	Flood Event	Date of Flood Event	Document used	Amount of flood	Comment
Rivers						
The Nanny River						
210	Nanny Duleek	Aug-86	26 Aug '86	Hand written report of hydrometric surveyor	While the bridge u/s of GS was flowing almost full, the flood water was also flowing across the road at 150 yards towards Drogheda with 1ft depth, and 350 yards towards Ashbourne.	All roads around Millrace State was flooded.
525	Nanny Beamount Bridge, Duleek	Nov-00	6 Nov '00	R150 Road Imp Sch - Phase I, Assess of Impact on floodplain, 11 Jul '03	WL at Beamount Brdg = 14.6mOD; Qp = = 45 m3/s; flood return period less than 5 yrs as per the report	
1273	Nanny Duleek	Nov-00	5-6 Nov '00	Nanny Certified Drainage Scheme, 2001 & Preliminary Report of Nov 2000 flooding by the OPW Hydrometric Section	Stn 8011 = 19.94(?) mOD; Stn 8017 (U/S) = 20.16 mOD; Paramadden= 21.02mOD; Bellewstown = 13.19mOD; WL exceeds crest of the new weir at Stn 8011 which is at 20.04 m OD	The Nov '00 event was the highest recorded of all the records in the Duleek area since the flood relief scheme was completed in 1998 (OPW Report). Flood return period 13 to 60 yrs
1329	Nanny Duleek	Oct-93	7 Oct '93		Flood threatened the Abbeylands State for the first time in 1993.	
3552	Nanny Duleek	Sep-75	15 Sep '75			Duleek Flood Relief Scheme (1996). Consultants Report (Nicholas O'Dwyer) refers to flooding in Duleek Co Meath. A number of dated floods referenced. (Report Includes: Flood Extent, Flood Level, Flood Depth, Source, Cause)
3553	Nanny Duleek	Dec-78	28 Dec '78			
3554	Nanny Duleek	Mar-80	18 Mar '80			
3555	Nanny Duleek	Sep-84	23 Sep '84			
3556	Nanny Duleek	Jan-92	Jan-92			
3557	Nanny Duleek	Jun-93	11 Jun '93			
3784	Nanny Duleek	Dec-54	8 Dec '54	Nanny Certified Drainage Scheme - EIS; RPS Cairns Ltd.	The most sever flood which occurred in 1954 washed away bridge on the Drogheda Road	
10341	Nanny Balrath Cross	Jan-07	18-Jan-07	Area Engineer Report P4D403A	Flooding occurs 1-2 times a year due to insufficient capacity of the arch bridge on Balrath cross road on N2/R153	
696	Nanny Balrath Cross Roads on N2/R153	Recurring		MCC - MOM, 14/3/05	Some of the arches of the Nanny Road Bridge are blocked and bridge does not have the capacity for volume of water. N2 flood January 2005. Flood occurs 1 to 2 times a year	
703	Nanny Kentstown on R153	Recurring		MCC - MOM, 14/3/05	River Nanny overflows its bank after heavy rain. Road is liable to flood. Some of the arches of the road bridge are blocked. This occurs 2 or 3 times per year	
705	Nanny Kentstown	Recurring		MCC - MOM, 14/3/05	Extensive area flooded by River Nanny. Some of the arches of the road bridge are blocked. No road is affected	
883	Nanny Beaumont to Julianstown	Recurring		MCC - MOM, 17/1/06	River Nanny flood plain. Floods 2 to 3 times per year.	
884	Nanny Balrath Cross to Duleek	Recurring		MCC - MOM, 17/1/06	River Nanny flood plain. Floods 2 to 3 times per year.	
2369	Nanny Follistown Meath	Recurring				
704	Danestown	Recurring		MCC - MOM, 17/1/06	Tributary of the Nanny River u/s of confluence with Hurley over flows its bank. Road is liable to flooding. This occurs 2 or 3 times per year	
The Hurley River						
2307	Hurley North Ashbourne	25-Aug-86	25-Aug-86	OPW Review Report-Aug '86 flood	There was extensive flooding north of Ashbourne on the Hurley river tributary and the stretch of the main river between Duleek and Julianstown was a vast lake with many farms and roads under water.	
715	Hurley Rathfeigh	Recurring			Hurley River near N2 crossing (d/s) east to Rathfeigh	
873	Hurley Coolfore to Rath Cross	Recurring			Hurley River near N2 crossing (u/s) north to Ashbourne	
871	Primatestown	Recurring			Hurley River Tributary, adjacent to N2, west to Garristown	
NA	Borranstown	Recurring	2002, 2003	Brendan - local residence, e-mail dated 4 Feb 09 (FCC forwarded)	Old (under capacity) bridge on the Hurley on Ashbourne-Garristown Road at Borranstown was blocked in 2003, causing local flooding, road closed temporarily	

Table B-3-1: List of historic fluvial flooding events in the study area (continued…)

The Broadmeadow River						
1263	Broadmeadow Swords	Aug-86	26-Aug-86			
1693	Broadmeadow Ashbourne	Aug-86	26-Aug-86	EPA - Flooding in the Broadmeadow catchment	Estimated WLs at Aug '86 flooding at Stn 08007 Ashbourne = 1.97m	Flooding in the Broadmeadow Catchment in Nov '02 was worse than the flooding of 1986 due to Hurricane Charlie.
1697	Broadmeadow Fieldstown	Aug-86	26-Aug-86	EPA - Flooding in the Broadmeadow catchment	Estimated WLs at Aug '86 flooding at Stn 08003 Fieldstown = 2.32m	
347	Broadmeadow Ashbourne	Nov-02	15-Nov-02	EPA - Flooding in the Broadmeadow catchment	Estimated WLs at Nov '02 floods: Stn 08003 Fieldstown = 2.51m; Stn 08007 Ashbourne = 2.62m	
2232	Dunshaughlin East	Nov-00				
874	Broadmeadow Robertstown	Recurring			At 2 km d/s of Ashbourne near Robertstown bridge	
3535	Broadmeadow recurring 1950s	Recurring	1940s and 1950s	Letters from Public Representatives	Flooding of houses and land at Warblestown, Swords, and public road in the vicinity by the Broadmeadow River.	
869	Fairyhouse Baltrasna	Recurring			Broadmeadow Tributary south of Ashbourne at R125 crossing	
870	Fleenstown	Recurring			Broadmeadow Tributary south of Ashbourne at N2 crossing	
The Ward River						
1630	Ward North Street Swords	Nov-02	14 & 15 Nov '02	FCC report on the Nov '02 flood	Ward River severely flooded roads between North St, and Watery Lane in Swords	
1639	Rowlestown, Ashbourne Road, Swords	Nov-02		FCC Minutes of Meeting, 04/04/05	Flooding at Swords – Ashbourne Road at Rolestown. Road was impassable. Part of school building flooded	
3534	Kilossery Rowlestown Swords	Jan-48				
1689	N2 at Coolquay Ward Road	2000		FCC Report on 2000 & 2002 floods	Road and Property flooded	
1702	N1 at Roundabout at Fingallions	Nov-02		FCC Report on 2000 & 2002 floods	Flooding occurred due to high water level in the Ward.	
1638	Balheary Road Swords	Recurring		FCC Minutes of Meeting, 04/04/05	In 2002 road blocked due to flooding at two locations. On other occasions road flooded but kept open.	
875	Kilbridge	Recurring			Ward River between N2 and N3	
The Mayne River						
677	Mayne Balgriffin Park	Jun-93	11-Jun-93	Correspondence related to flooding at Balgriffin Dublin.	5 Balgriffin Park was badly flooded to a depth of 4 ft according to their letter. The local objected the proposal of discharging surface water from 900 houses to the Mayne River at Hole In the Wall, Balgriffin.	
2178	Mayne M50 flyover old Airport Road	Nov-00		FCC Report on 2000 & 2002 floods; Minutes of meeting	Stream floods road at this location fairly frequently. Remedial works carried out in 2004.	
2180	North of M50 (N1 road) old Airport Road	Nov-02		FCC Report on 2000 & 2002 floods; Minutes of meeting	Stream floods road at this location fairly frequently. Remedial works carried out in 2004.	
240	Grange Stream, Baldoyle (Mayne Tributary)	Dec-54		Dublin City Council memo.	Extent of flooded area in Baldoyle, Dublin during Dec 1954 and other information related to the flooding.	
1463	Mayne River Bridge Baldoyle	Recurring		Baldoyle Flood Relief Scheme	Flooding due to incapacity of Mayne River Bridge during high tides. Flood Relief Scheme completed in 2001.	
1620	Mayne M50 flyover old Airport Road	Recurring		FCC Report on 2000 & 2002 floods; Minutes of meeting	Stream floods road at this location fairly frequently. Remedial works carried out in 2004.	
The Delvin River						
348	Delvin Naul	Nov-02	15 Nov '02	EPA - Flooding in the Delvin catchment, Nov '02	WL at the Naul GS 08002 on 15 Nov '02 flooding event was estimated as 1.21m.	
1261	Delvin Naul	Aug-86	26 Aug '86	Hurricane Charlie - An Overview; An Foras Forbartha, 16 Nov 87	Highest flow on record, Qp = 5.2 m3/s	
1698	Delvin Naul	Dec-78	27 Dec '78	EPA - Flooding in the Delvin catchment, Nov '02	During 27 Dec '78 flooding at Skane catchment, Naul GS WL was recorded as 1.51m.	
942	Delvin Stamullin	Recurring		MCC area Engineer Report; MOM of 17 Jan '06	Delvin overflows its banks after heavy rain at Stamullin. Flooding occurs 2 to 3 times per year, flooding the road.	
961	Station Road, Gormanstown	Recurring			Delvin River near railway crossing	
1264	Garristown Steam (Tributary of Delvin)	Aug-86	26 Aug '86	An Foras Forbartha, 16 Nov '87	WL (at GS) = 0.9 m on 26 Aug '86	

Table B-3-1: List of historic fluvial flooding events in the study area (continued)

The Sluice River						
1262	Sluice Kinsaley Hall	Aug-86	26 Aug '86	Hurricane Charlie - An Overview; An Foras Forbartha, 16 Nov 87	WL = 1.18 m on 26 Aug '08	
1616	Kinsealy Lane Area	Oct-02	20 - 21 Oct '02	FCC Report	Two houses on the Cul-de-sac off Kinsaley lane were flooded with 1 ft water. The Sluice also flooded Chapel Rd, Kinsaley Lane, Junction of Drimnigh Road/The Hill Station Rd.	
1613	Sluice River Strand Road Portmarnock	Recurring		FCC Minutes of Meeting, 04/04/05	Flooding at Portmarnock Bridge due to combination of high tides and high river flow. Road raised by 380mm in 2004 which should rectify problem. (Flood ID No 1613)	
1933	Sluice River Kinsealy Lane	Recurring		FCC Report-Keay area of flooding, Sept 01	Extensive flooding occurs on Kinsealy Lane due to the overflowing of the Sluice River, as a result of road culvert & blockage along the stream	
NA	Sluice River, Kinsealy	Nov-00	6 Nov '00	Hydrological Study of Sluice River at Kinsealy - JBA Report, Mar '01	Staff gauge record 11.4 m OD, JBA hydraulic model estimated WL = 11.78 m OD	
NA	Hazelbrook Stream (Sluice Tributary)	Mar/Aug 08	March & 9 & 16 Aug 08	Peter Coyle and neighbours e-mail dated 11 Feb 09	Flooding of the property noticed 3 times in 2008. Never seen previously for the last 9 years. As suggested, flooding problem could be due to water pumping their drain from the main system.	
NA	Sluice River, Kinsealy	Aug-08		Peter Coyle and neighbours e-mail dated 11 Feb 09	Flooding near Abbey Wall State, Kinsealy Village. Floods were only couple of inches getting the house of Louisa Goodliffe (in the nes state).	
The Mornington River						
651	Mornington	Nov-00	6th Nov '00	Mornington District SW & Flood Protection Scheme, Jan 04, Kirk McClure Morton	Qp = 2.98 m3/s	1: 20 year return period according to the report
652	Mornington	Feb-02	1st Feb 2002	Mornington District SW & Flood Protection Scheme, Jan 04, Kirk McClure Morton	Tidal flood, existing defence embankment d/s of Lady's Finger overtopped by 0.25 m	Tidal 1:100 yrs combined with storm serge 1:25 yrs & fluvial 1:1yr, according to the report.
2217	Mornington/Bettystown	Nov-00	16 Nov '02	Mornington District SW & Flood Protection Scheme, Jan 04, Kirk McClure Morton	Combination of high tides and high rainfall that occurred on the 6th November 2000. Properties are affected.	
5300	Mornington	Feb 2002 1		Photographs of Feb 2002 flood		
5302	Mornington	Feb 2002 2		Photographs of Feb 2002 flood		
5303	Mornington	Feb 2002 3		Photographs of Feb 2002 flood		
5304	Mornington	Feb 2002 4		Photographs of Feb 2002 flood		
940	Mornington West	Recurring			Morning River u/s of its outfall to the Boyne Estuary	
941	Piltown Meath	Recurring			Mornington tributary west of Bettystown near railway crossing	
The Ballyboghil River						
1621	Ballyboughal on Naul Road	Nov-02		FCC MOM; Photographs	Serious flooding at the junction of Oldtown Road and R108. Flooding of road and 1 house in November 2002.	
1936	Ballyboughal	Recurring				
NA	Ballyboughal area flooding	Recurring	1986, Nov 02, 10 Jan '08, 31 Mar '08	Brendan P Lynch - Flood Info	Photographs of historical flooding in the Ballyboughal area, roads, bridges during the 1986, Nov 02 and Jan/Mar '08 flooding events	
The Mill Stream						
1265	Mill Skerries	Aug-86	26-Aug-86	An Foras Forbartha, 16 Nov '87	WL = 0.9m, highest flow on record	
2131	Mill Stream Skerries	Nov-82	5th, 6th & 7th Nov '82	Dublin Co Co Report-Nov 82 flood	Flooding at Mill Stream was minor compared with that of 1978. Overflow of SW u/s of the railway culvert, and overtopping of the banks of the river d/s of this point caused flooding.	55.1mm rainfall in 24 hrs and 45.2 mm in 12 hrs at Dublin Airport.

Table B-3-1: List of historic fluvial flooding events in the study area (continued…)

The Gaybrook Stream						
2164	Gaybrook Stream (Melrose Park)	Oct-02	20 & 21 Oct 02	FCC Flooding Report	Development in Organon seemed to stop the progress of surface water ditch, which then overflows and floods wasteland between Organon and Melrose Park and resulted in the flooding of No. 18 The Drive.	
NA	Gaybrook St (Kinsealy Court)	Aug-08	9 Aug '08	E-mail of Peter Coyle dated 11/02/09	Flooding at Aspen Drive, Kinsealy Court. Flood originated rear/side of No. 1 & went the street affecting both sides. Photo and VDO record available.	
The St. Catherine's Stream						
1684	Loughshinny Rush	Nov-00	5-7 Nov '00	FCC - MOM, 9/12/2002	Rush/Loughshinny road flooded due to the under capacity of the existing culvert. It is exacerbated by a foul sewer d/s outlet of the culvert which further constrict flows.	
The Corduff Stream						
1640	Corduff Stream Blake's Cross Lusk	Recurring		FCC Minutes of Meeting, 04/04/05	Flood in Corduff Stream at Blakes Cross, Lusk. Road floods due to heavy rain. Bridge is under capacity.	
NA	Ballough River -Tributary of Corduff Stream		9-10 Aug 2008	Aidan Reid,	Flooding of townlands of Ballough, Ballystrane and Baldrumman, Lusk, from 1982 to date in relation to a proposed Motorway Service Station at M1-Baldrumman	
The Rushtown Stream						
1624	Brooke Stream Skerries Road, Rush	Recurring		FCC Minutes of Meeting, 04/04/05	Rushtown Stream crossing by R128 at Rush. Brooke Stream floods road making it impassable	

Table B-3-2: List of historic pluvial flooding events in the study area

Flood ID	Place of flooding	Date/type of flooding event	Location		Type of flooding
			Easting	Northing	
674	Carrickbrack Road Sutton	Recurring	326348	238993	Low lying land
697	Brien's Cross on N2/R150	Recurring	299308	266675	Low lying land
722	Gillstown CR 379/380	Recurring	292983	264549	Low lying land
950	Boolies Little R152	Recurring	304365	265476	Low lying land
952	Princetown, Balgeeth	Recurring	305436	261559	Low lying land
953	Stamullin	Recurring	314381	265402	Low lying land
954	Martin's Road, Gormanstown	Recurring	317235	266755	Low lying land
955	Clinstown Cross	Recurring	313143	264278	Low lying land
956	Irishtown, CR 438 A	Recurring	316165	268337	Low lying land
957	Irishtown CR 438 B	Recurring	315920	269469	Low lying land
958	Donacarney School R150	Recurring	313796	274556	Low lying land
959	Colp West	Recurring	312301	274112	Low lying land
960	Mosney Road	Recurring	315680	268963	Low lying land
962	Minnistown	Recurring	314637	272335	Low lying land
963	Alvera Heights, Laytown	Recurring	316239	271628	Low lying land
1180	Irishtown CR 438 C	Recurring	315667	270275	Low lying land
1457	Ballisk Lane Donabate	Recurring	322746	249948	Low lying land
1459	Pinnock Hill Swords	Recurring	317972	245867	Low lying land
1460	Balrothery Balbriggan	Recurring	319470	260808	Low lying land
1468	Pinnock Hill	Oct-02	317972	245867	Low lying land
1621	Ballyboughal on Naul Road	Nov-02	314923	253852	Low lying land
1623	Whitestown Road Rush	Recurring	324696	253588	Low lying land
1634	Cobb's Lane Donabate	Recurring	320917	250062	Low lying land
1636	Corballis Road Donabate	Recurring	324429	248444	Low lying land
1637	Balleally Lane	Recurring	322815	252696	Low lying land
1649	Naul Balbriggan Road, Dalahassey	Recurring	317472	262236	Low lying land
1651	Stockhole Lane (near Airport)	Recurring	318808	242667	Low lying land
1710	Hearst Road Donabate	Nov-02	322619	249992	Low lying land
1711	Beaverstown	Nov-02	322703	251170	Low lying land
1650	The Square Naul Village		313231	260956	Runoff
1663	Kilshane Cross	Nov-02	311319	242743	Runoff
1688	N1 at Blake's Cross and Turvey Ave	Nov-00	319836	250536	Runoff
1709	Ballisk Donabate	Nov-02	322746	249948	Runoff
1715	The Grange Road Baldoyle	Oct-02	324082	240102	Runoff
2128	Rathingle Swords	Nov-82	316861	245813	Runoff
2129	Seatown Villas Swords	Nov-82	318544	247244	Runoff
2130	Pine Grove Park Swords	Nov-82	317452	247532	Runoff
2165	Biscayne Coast Road Malahide	Oct-02	324109	245581	Runoff
2173	Spout Road Rogerstown/Rush	Aug-04	324404	253568	Runoff
2191	Pinnock Hill	Nov-02	317972	245867	Runoff
2212	Grange Road Donaghmede	Nov-82	323362	240159	Runoff

Table B-3-3: List of historic tidal/coastal flooding events in the study area

Flood ID	Place of flooding	Date of flooding event	Location	
			Easting	Northing
882	Laytown	Recurring	316148	271189
1458	Rogerstown Rush	Recurring	324100	253067
1462	Baldoyle Coastal	Recurring	324140	241128
1617	Seabank (Estate) Court Malahide	Recurring	323507	246059
1618	Bisset Strand and Estuary Road Malahide	Recurring	321087	246633
1627	Spout Road Rogerstown/Rush	Recurring	324404	253568
1628	The Burrow Portrane	Recurring	324788	251540
1629	Brooke Stream Millers Lane Skerries	Recurring	324909	259568
1632	Ballymadrough Donabate	Recurring	320444	248524
1635	Turvey Avenue Belfast Road Dublin	Recurring	319836	250536
1648	Bremore Balbriggan	Recurring	319632	264462
1712	Covetown Balbriggan	Nov-02	319876	264116
1713	Bath Road	Nov-02	320127	264257
1732	Dublin Road Sutton	Feb-02	325182	239280
1738	Mill View Lawn Malahide	Feb-02	321218	246157
1742	Strand Road Malahide	Feb-02	324697	244173
1747	Estuary Road Swords	Feb-02	319180	247709
1749	Gartan Court Swords	Feb-02	319189	247568
1753	Crescent South Shore Rd Rogerstown	Feb-02	325292	253230
1755	The Burrow Portrane	Feb-02	324321	252498
2872	Skerries South Beach Holmpatrick	Feb-02	325732	260041
5321	Laytown	Feb-02	316148	271189

Table B-4: Priority list of hydrometric station for reinstallation

Station	Responsibility	Station Name	River Name	Catchment area, km^2	High flow rating quality	E	N	Status
08002	FCC	Naul (new)	Delvin	37.0	A1	313115	261136	Data logger installed on 14/12/2009
08010	FCC	Garristown S.W.	Garristown Stream	1.13	C	307869	258933	Data logger installed on 18/11/2009
08012	FCC	Ballyboghill	Ballyboghill	22.1	B	315029	253649	Being upgraded by FCC
08006	FCC	Hole in the Wall	Mayne	16.0	?	322191	241431	Priority 2*
08005	FCC	Kinsaley Hall	Sluice	10.1	A2	322114	243105	Priority 1*
08009	FCC	Balheary	Ward	62.0	A1	318579	248027	Priority 1*
08004	FCC	Owen's Bridge	Ward	36.6		310405	245857	Priority 2*
08003	FCC	Fieldswtown	Broadmeadow	76.2	B	311780	250212	Priority 2*
8014	FCC	Skerries	Mill Stream	8.2		324925	259585	Priority 2*
08007	MCC	Ashbourne	Broadmeadow	34.0	B	305926	252256	Priority 1*
08008	OPW	Broadmeadow	Broadmeadow	108.0	A2	317453	248652	In operation
08011	OPW	Duleek	Nanny	191.0	B	305297	268519	In operation
08017	OPW	Duleek (u/s)	Nanny	187		305185	268453	
NA	DAA	Cuckoo	Cuckoo (Mayne Tributary)					In Operation

In Operation =	**5**
Being upgraded by FCC =	**1**
Proposed for upgrade (Priority 1 & 2) =	**7**
Non priority	**1**
Total	**14**

FCC	9
MCC	1
OPW	3
DAA	1
Total	**14**

Note:
Priority 1* = First Priority
Priority 2* = Second Priority

Note: *FCC: Fingal County Council* *MCC: Meath County Council* *OPW: Office of Public Works* *DAA: Dublin Airport Authority*

Appendix C: Hydrometric analysis

C1 Rating curve review

C1.1 Station 08002 Naul on the Delvin River

Hydrometric Station 08002 Naul is located approximately 50m upstream of the R108 Naul Bridge (old arch bridge) on the Delvin River. The station is located on the left bank of the river on a shallow weir (See Figure C-1). The datum of the gauging station is 61.618 m OD Poolbeg (58.905m OD Malin Head). This gauging station is now obsolete. A weir has been constructed approximately 80m downstream of the old gauging station (30m downstream of the R108 Bridge). According to the EPA, a data logger has been installed at this weir on 14 December 2009.

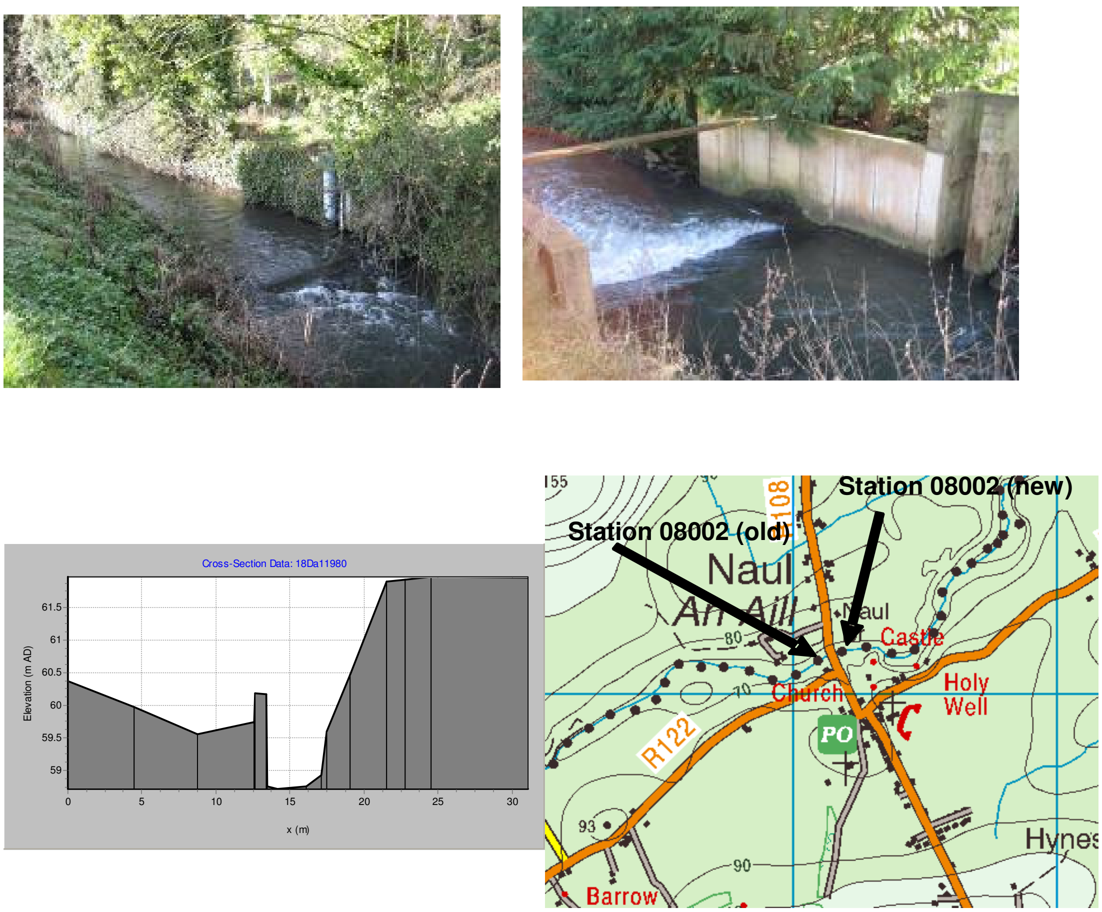


Figure C-1: Station 08002 Naul: photo of the old station (top left) and the new weir (top right), channel cross section of the old station and locations of the old and new stations

The channel reach at the gauging station is relatively straight. The left bank is relatively flat for approximately 10m, beyond which it has steep slope. The right bank is higher than the left bank, and has relatively flat overbank. A housing state is located on the right bank. The river bifurcates approximately 20m downstream of the gauging station, and after passing the R108 Bridge again combines to become one single channel.

The hydraulic model consists of 27 channel cross section, one bridge (the R108) and three weirs. The first weir is at the old gauging station, the second weir is the new gauging station and the third weir has a drop of approximately 4.0m. The downstream of this weir is the downstream extent of the model, which is represented by a spill. The weir is represented by ISIS spill unit and the bridge structure by a combination of ISIS bridge and spill unit. The ISIS model was calibrated against gauged data with adjustments to the Manning's roughness coefficient, n, and weir coefficient C. The results of the rating review and the revised rating are shown in Figure C-2 and Table C-1.

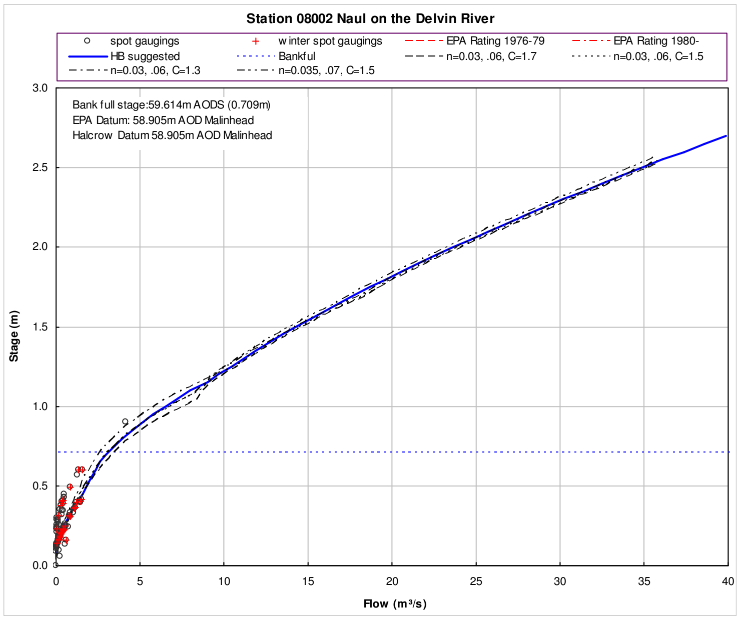


Figure C-2: Rating curve for Station 08002 Naul (old station) on the Delvin River

Table C-1: Parameters of the rating equation $Q(h) = C*(h+a)^b$ for Station 08002Naul (old)

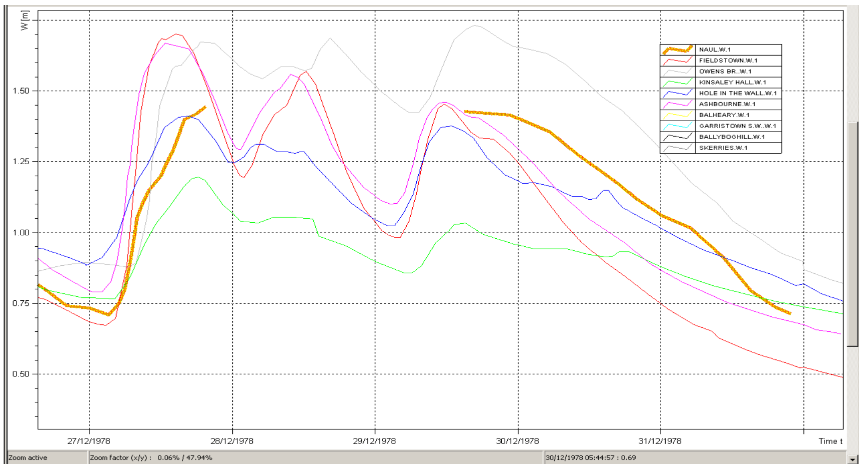
Section	Minimum stage (m)	Maximum stage (m)	C	a	b	Rating curve
1	0.088	0.125	18800	0	6.09	EPA
2	0.125	0.213	104	0	3.60	EPA
3	0.213	0.427	7.4	0	1.92	HB
4	0.427	0.700	4.8	0	1.4	HB
5	0.700	1.120	6.5	0	2.2	HB
6	1.120	2.700	7.05	0	1.745	HB

It is observed from the rating curve (Figure C-2) that there is a clear shift in the EPA ratings 1976-'79 and post-1980. The ISIS based rating curve accurately represent the flow gauging up to 1.5m^3/s after which it slightly overestimates the flow in comparison to the EPA post-1980 (latest) rating curve.

The Q_{med} value for this gauging station, from the EPA rating was 3.77m^3/s. The HB proposed rating review determined the new Q_{med} value as 4.40m^3/s. With a catchment area of 37km^2, the specific Q_{med} (Q_{med} / $A^{0.77}$) is approximately 0.273m^3/s which is considered small in comparison to other stations in the study area.

The plot of full hydrograph at the highest recorded flood (28 December 1978, gauge height 1.51m) indicates a case of reverse spindle. The EPA was requested to check this value. The

EPA confirmed that there was a case of reverse spindle but the actual value can not be predicted. Instead, the EPA has treated this flood (28 December 1978) as a gap in the data and the largest available gauge height is 1.445m which occurred on the 29th of December 1978 (see Figure C-3 provided by the EPA). However, the present study has considered the originally provided gauge height of 1.51m as the largest flood on 28th December 1978.



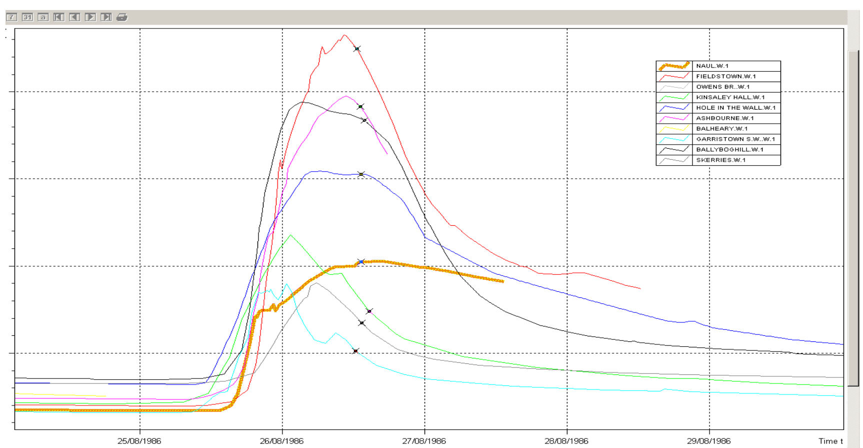


Figure C-3: Gauge heights at the flooding events of December 1978 (upper) and August 1986 (lower) at the EPA stations (provided by the EPA on 02 October 2009)

Figure C-3 (upper) clearly shows the gap in gauge height at Station 08002 Naul on 29 December 1978. It is noted that during the August 1986 event, Station 08002 Naul did not experience an extreme flood as demonstrated in Figure C-3 (lower).

C1.2 Station 08003 Fieldstown on the Broadmeadow River

Hydrometric Station 08003 Fieldstown is located approximately 30m upstream of the R122 Bridge on the Broadmeadow River, just to the north of the R122 and R125 crossing. The gauging station is an open channel section (See Figure C-4).

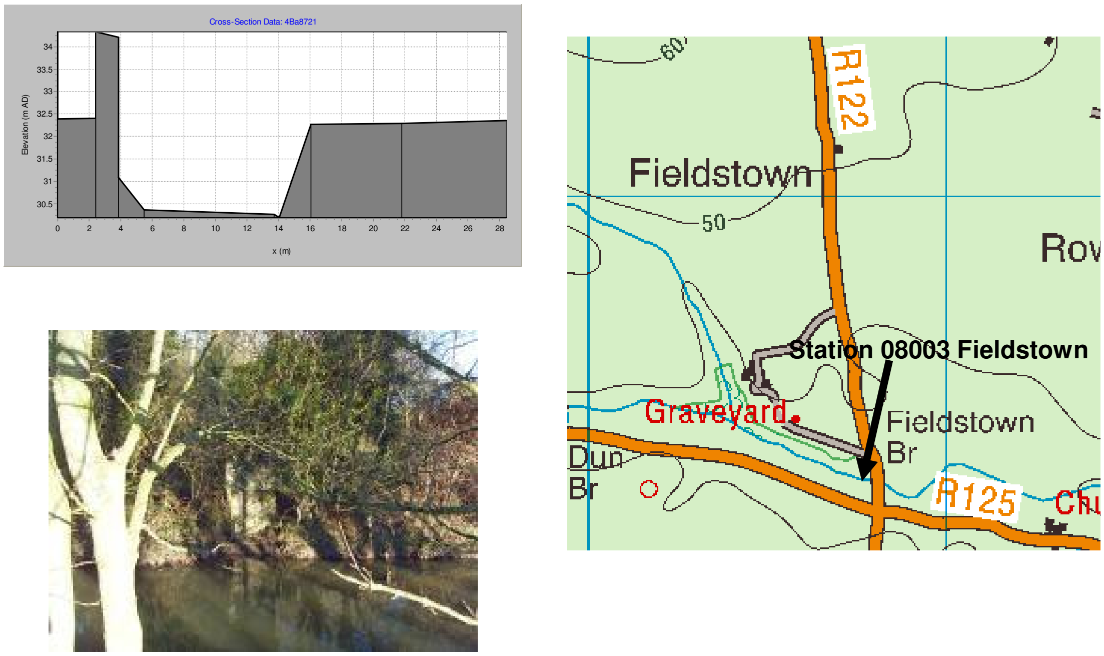


Figure C-4: Channel cross section, photo and location of Station 08003 Fieldstown

The cross section at this station is wide and relatively flat. The right bank has a wide floodplain and the left bank is relatively at higher elevation adjacent to the gauging station. A very slow moving pool of water was observed from the gauging station up to the R122 Bridge. It appears that the high flow regime at this station is affected by the obstruction of the R122 Bridge.

The datum of the station is reported to have been changed six times and the rating was changed 14 times between 1976 and 1992. This demonstrates the unstable regime of the river at the gauging station. The latest datum at this station is 33.039m OD (Poolbeg), i.e., 30.326m OD Malin Head, which is used for the review of rating in the present study.

The hydraulic model consists of 17 channel cross sections, one bridge (the R122) and one weir approximately 380m downstream of the bridge. The downstream boundary of the model consists of a normal depth boundary unit. The weir is represented by ISIS spill unit and the bridge structure by a combination of ISIS arch bridge and spill unit. The ISIS model was calibrated against gauged data with adjustments to the Manning's roughness coefficient, n and bridge coefficient C. The results of the rating reviewed and the revised rating are shown in Figure C-5 and Table C-2.

Table C-2: Parameters of the rating equation $Q(h) = C*(h+a)^b$ for Station 08003 Fieldstown

Section	Minimum stage (m)	Maximum stage (m)	C	a	b	Rating curve
1	0.000	0.332	52.20	0	3.69	EPA
2	0.332	0.600	12.0	0	2.24	HB
3	0.600	1.000	12.0	0	2.20	HB
4	1.000	1.500	12.06	0	1.9	HB
5	1.500	1.944	13.2	0	1.68	HB
6	1.944	2.550	11.7	0	1.85	HB

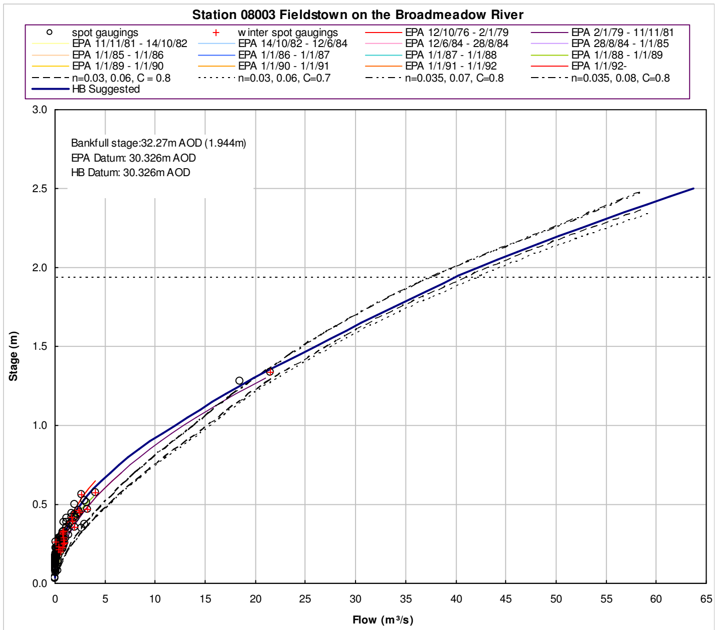


Figure C-5: Rating curve for Station 08003 Fieldstown on the Broadmeadow River

It is observed from Figure C-5 that, the model could not be well fitted with the low flow gauge values but fits with the median flow values. Therefore, for the low flows, the EPA latest rating curve is adopted.

The Q_{med} value for this gauging station, from the EPA rating is 19.9m^3/s and from the revised rating is also 19.9m^3/s. With a catchment area of 76.2km^2, the specific Q_{med} (Q_{med} / $A^{0.77}$) is approximately 0.706m^3/s. The gauge height from the flood mark of November 2002 flood was 2.51m which is equivalent to a flow of 64.21m^3/s. Similarly, the 1986 gauge height was 2.32m which is equivalent to a flow of 55.51m^3/s. These flood values are higher than those recorded at the downstream gauging station (Station 08008 Broadmeadow) on the same river having catchment area of 110km^2. The quality of most of the water level data available from the EPA has been flagged as “unchecked”. Considering the instability of the datum and the rating at this station, the obstruction created by the R122 Bridge and the exceptionally high flow values, the annual maximum series of this station is considered unreliable and is not used for further hydrological analysis.

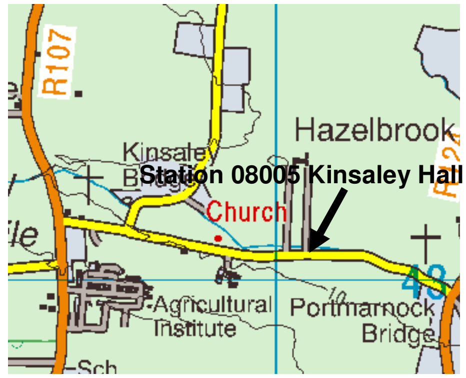
The station is not currently in operation. Since the flow regime of the gauging station is affected by the R122 Bridge, it is recommended that this station is moved from its present location to a more suitable location.

C1.3 Station 08005 Kinsaley Hall on the Sluice River

Hydrometric Station 08005 Kinsaley Hall on the Sluice River is located downstream of two old bridges at Kinsaley Hall. The gauging station is situated within the premises of a private property at Kinsaley Hall. Access to the station required permission from the property owner. The gauging station is located upstream of a shallow weir (See Figure C-6).

The channel section appears to have limited capacity; therefore overbank flow is expected even at median flood flows. The two bridges located just upstream of the station have limited flow capacity. The Kinsaley Lane, located approximately 0.5km upstream of the gauging station has a history of recurring flooding from the Sluice River.

The datum of the gauging station is 6.473m OD Poolbeg, i.e., 3.76m OD Malin Head. The EPA rating curve changed 4 times between 1976 and 1983. The station is currently not in operation.



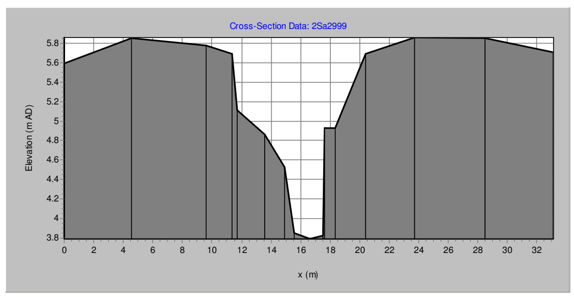


Figure C-6: Photo, location and channel cross section of Station 08005 Kinsaley Hall

The hydraulic model consists of 16 channel cross sections, two small bridges next to each other and one weir at the gauging station. The downstream boundary of the model consists of a normal depth boundary unit. The weir is represented by ISIS spill unit and the bridge structure by a combination of ISIS arch bridge and spill unit. The ISIS model was calibrated against gauged data with adjustments to the Manning's roughness coefficient, bridge coefficient and weir coefficient. The results of the rating reviewed and the revised rating are shown in Figure C-7 and Table C-3.

Table C-3: Parameters of the rating equation $Q(h) = C*(h+a)^b$ for Station 08005 Kinsaley Hall

Section	Minimum stage (m)	Maximum stage (m)	C	a	b	Rating curve
1	0.161	0.190	65689900	0	12.95	EPA
2	0.190	0.287	72.42	0	4.68	EPA
3	0.287	0.550	4.04	0	2.37	EPA
4	0.550	0.770	3.50	0	2.00	HB
5	0.770	0.950	5.25	0	3.70	HB
6	0.950	1.200	4.75	0	1.95	HB
7	1.200	1.500	3.70	0	3.10	HB

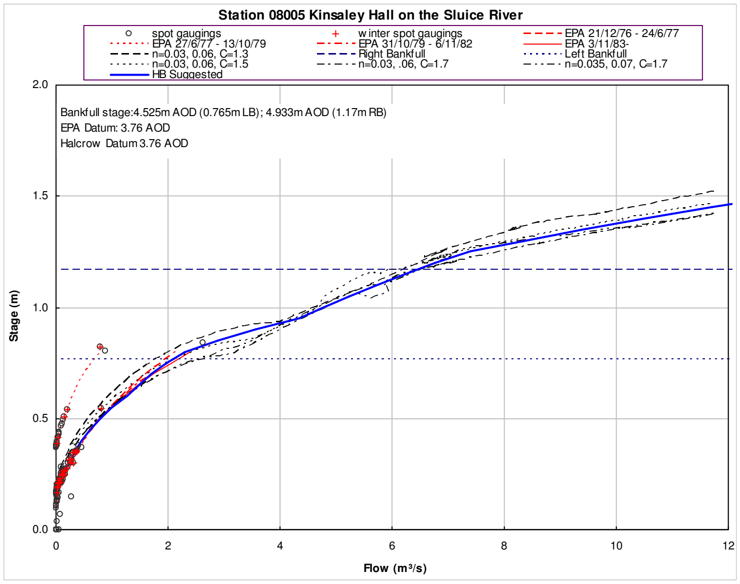


Figure C-7: Rating curve for Station 08005 Kinsaley Hall on the Sluice River

The ISIS model fitted well with the median flows, with flow values up to 2.6m^3/s. However, the low flow is slightly underestimated by the ISIS based rating curve. Therefore for the low flow regime, the EPA rating curve is adopted and for the high flow, the ISIS based rating is proposed.

The Q_{med} value for this gauging station, from the EPA rating was 2.76m^3/s and from the revised rating is 3.17m^3/s. With a catchment area of 10.1km^2, the specific Q_{med} is approximately 0.534m^3/s.

Due to the access problems at this gauging station, it is recommended that this station is moved to a more suitable location further upstream.

C1.4 Station 08007 Ashbourne on the Broadmeadow River

Hydrometric Station 08007 Ashbourne on the Broadmeadow River is not currently in operation. It was also difficult to locate the exact position of the old station on the ground. Meath County Council assisted in locating its correct position, which is between two new arch bridges near Ashbourne (See Figure C-8).

Figure C-8: Photo, location and channel cross section of Station 08007 Ashbourne

The River appears to have been slightly realigned downstream of the old gauging station to accommodate the new bridges. The datum of the gauging station changed nine times between 1977 and 1995 and the rating curve changed three times. The latest datum of the gauging station is 64.08m OD Poolbeg, i.e., 61.367m OD Malin Head, which was used for the rating review.

The hydraulic model consists of 14 channel cross sections and three bridges. The bridge structures are modelled by a combination of ISIS arch bridge and spill units. The ISIS model was calibrated against gauged data with adjustments to the Manning's roughness coefficient, and bridge coefficient. The results of the rating reviewed and the revised rating are shown in Figure C-9 and Table C-4.

Table C-4: Parameters of the rating equation $Q(h) = C*(h+a)^b$ for Station 08007Ashbourne

Section	Minimum stage (m)	Maximum stage (m)	C	a	b	Rating curve
1	0.000	0.265	9391.6	0	8.70	EPA
2	0.265	0.593	6.22	0	3.20	EPA
3	0.593	1.000	4.15	0	2.45	HB
4	1.000	1.500	4.15	0	2.175	HB
5	1.500	2.200	4.50	0	2.04	HB
6	2.200	2.800	5.10	0	1.90	HB

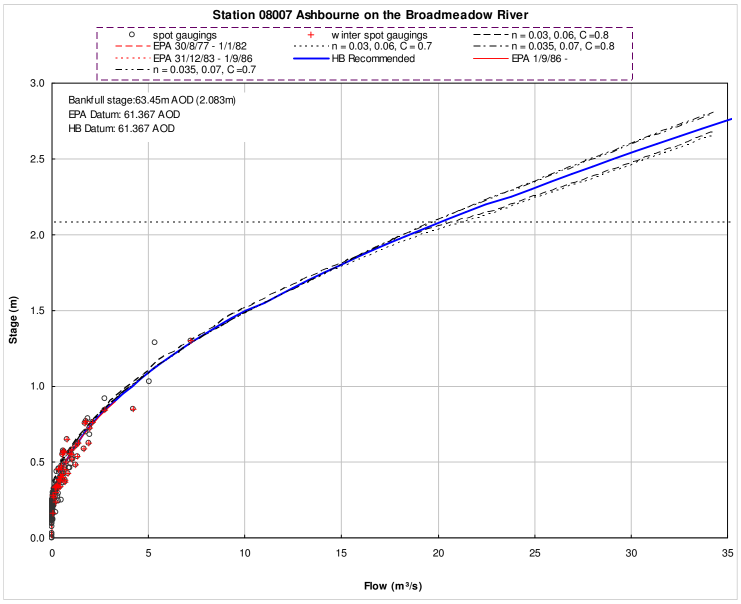


Figure C-9: Rating curve for Station 08007 Ashbourne on the Broadmeadow River

It is observed from Figure C-9 that the ISIS based rating curve fitted well with all the gauge flows. At low flow regime, the ISIS based rating slightly underestimated the flow and hence the EPA latest rating was adopted. For the high flow regime the ISIS based rating was adopted.

The Q_{med} value from the EPA rating was 9.14m^3/s and from the revised rating it is 8.16m^3/s. With a catchment area of 34km^2, the specific Q_{med} is approximately 0.54m^3/s.

C1.5 Station 08008 Broadmeadow on the Broadmeadow River

Hydrometric Station 08008 Broadmeadow on the Broadmeadow River is one of the two stations installed by the OPW and still in operation in Hydrometric Area 08. The gauge is located on the right bank of the Broadmeadow River at Broadmeadow, to the north of Swords. The gauge is installed on a permanent weir with a low flow channel (see Figure C-10).

The gauge can be accessed by a small local road on the right bank of the river. The weir and the gauging station can also be viewed clearly from the left bank which is within a private property. The river is relatively straight and the channel is well represented at the gauging station location. There are no flow restrictions for at least 500m upstream and downstream of the gauging station. The low flow weir crest level varies from 5.927 to 5.938m OD Malin Head whereas the OPW datum is 8.65m OD Poolbeg, that is, 5.937m OD Malin Head.

The ISIS hydraulic model consists of 15 channel cross sections and one weir at the gauging station. The weir is modelled as an ISIS spill unit. The ISIS model was calibrated against gauged data with adjustments to the Manning's roughness coefficient and spill coefficient. The results of the rating reviewed and the revised rating are shown in Figure C-11 and Table C-5.

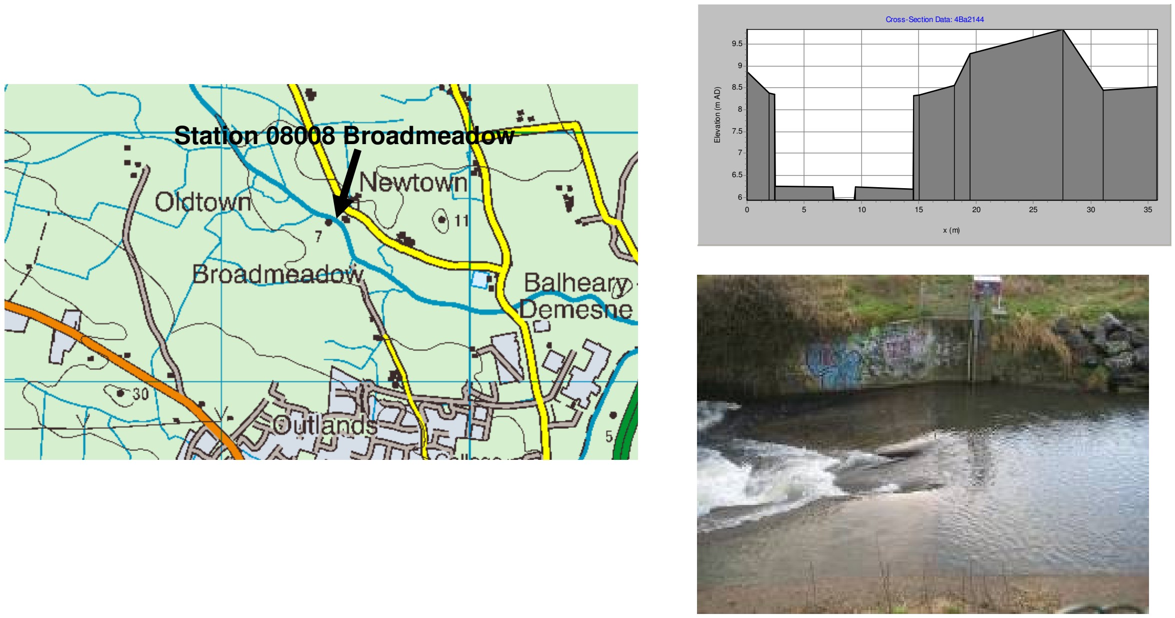


Figure C-10: Location, photo and channel cross section of Station 08008 – Broadmeadow

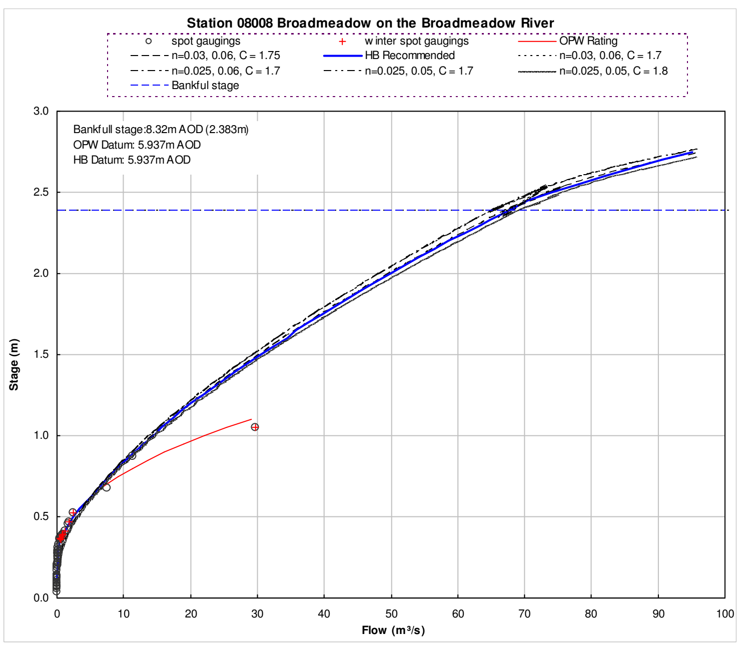


Figure C-11: Rating curve for Station 08008 Broadmeadow on the Broadmeadow River

It is observed from Figure C-11 that the ISIS based rating curve fitted well with the second and the third largest spot flow but not the largest spot flow. The OPW has been requested to verify this largest spot flow value. Although the OPW has confirmed that there was no error with this spot flow, there are no other similar spot flows to support this spot flow value. The model was simulated with the lowest value of Manning's roughness coefficient and highest value of weir co-efficient but still could not replicate the largest flow, although it matches well with the second and third largest flow.

Table C-5: Parameters of the rating equation $Q(h) = C*(h+a)^b$ for Station 08008 Broadmeadow

Section	Minimum stage (m)	Maximum stage (m)	C	a	b	Rating curve
1	0.108	0.286	1.02	0	1.50	OPW
2	0.286	0.417	70.00	-0.15	3.06	OPW
3	0.417	0.600	33.00	-0.15	2.49	OPW
4	0.600	1.000	14.60	0	2.15	HB
5	1.000	1.600	14.30	0	1.87	HB
6	1.600	2.400	15.25	0	1.71	HB
7	2.400	2.750	6.85	0	2.60	HB

The OPW high flow rating curve is based on the extrapolation of the joining the largest (SG 1.05m and Q of 29.75m^3/s on 31/01/1980) and the third largest spot flows, but it ignores the second largest spot flow. A rating curve based on such extrapolated line produces exceptionally high flow value, for example the 13th November 2002 flow value is 124m^3/s (for a gauge height 1.85m). The Q_{med} from the OPW rating curve is 39.10m^3/s which gives specific Q_{med} value of 1.05m^3/s. This is approximately double the value of specific Q_{med} at Ashbourne (0.54m^3/s). On the other hand, the Q_{med} value from the Halcrow Barry suggested rating curve is 21.06m^3/s and the specific Q_{med} is 0.564m^3/s, which is close to that of Station 08007 Ashbourne.

The photograph in Figure C-10 shows that the gauging station is located right on the weir crest, i.e., within the drawdown area of the weir. The current industry practice is to locate the gauge upstream of the weir crest at approximately 3 to 4 times the weir height. Therefore it is recommended to move the gauge upstream of the weir by a distance of 3 to 4 times the weir height.

C1.6 Station 08009 Balheary on the Ward River

Hydrometric Station 08009 is located on the left bank of the Ward River just upstream of the Balheary fish-pass (See Figure C-12). It is located approximately 220m upstream of the old N1 (now R132) Bridge. The gauging station is now obsolete. The Balheary fish-pass is accessible from the R132 and a footpath along the left bank of the Ward River.

The EPA provided datum on 17/04/1980, 30/08/1098 and 27/08/1993 are 3.304m OD, 3.224m OD and 3.204m OD (Malin Head) respectively. The latest datum of 3.207 m AOD is 0.033m below the weir crest of 3.24m OD. As the fish-pass is permanent in nature, it is assumed that the datum is the crest of the low flow weir of the fish-pass at 3.24m OD. The rating review is carried out with respect to this datum of 3.24m OD (Malin Head).

The Ward River is tidal at the R132 Bridge, therefore the downstream extent of modelling does not extend up to this bridge. A short span bridge exists approximately 120m d/s of the fish-pass. This bridge is quite high and does not seem to obstruct the high stage flow. A footbridge is located approximately 380m u/s of the station which also does not obstruct the high stage flow.

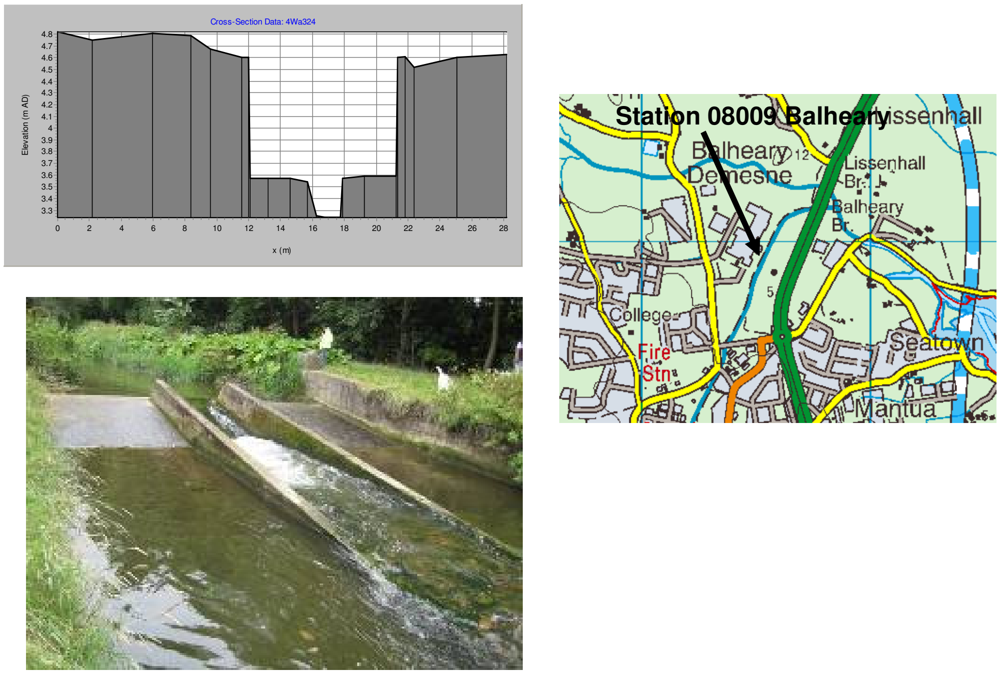


Figure C-12: Channel cross section, photo and location of Station 08009 –Balheary

The ISIS river model is fitted with 14 river cross sections and one fish pass. The fish pass is modelled as an ISIS spill unit. The downstream boundary of the model consists of a normal depth boundary unit. The ISIS model was calibrated against gauged data with adjustments to the Manning's roughness coefficient and weir coefficient. The results of the rating reviewed and the revised rating are shown in Figure C-13 and Table C-6.

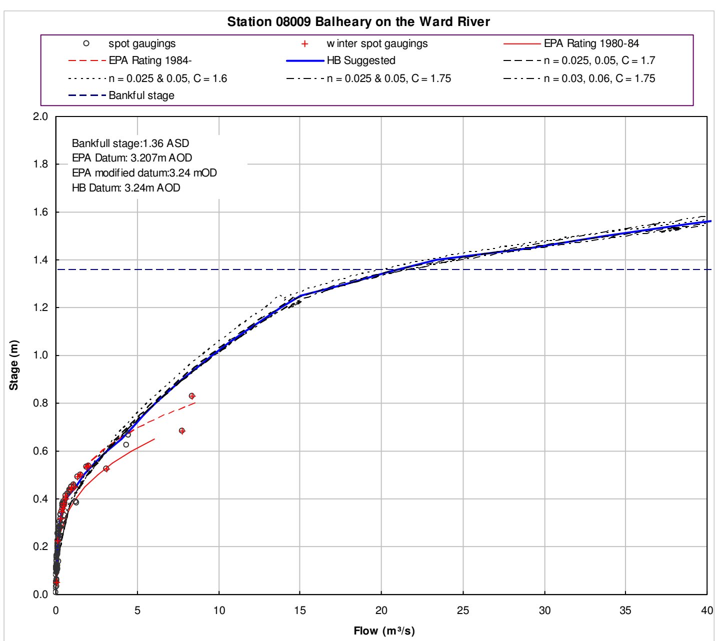


Figure C-13: Rating curve for Station 08009 Balheary on the Ward River

Table C-6: Parameters of the rating equation $Q(h) = C*(h+a)^b$ for Station 08009 Balheary

Section	Minimum stage (m)	Maximum stage (m)	C	a	b	Rating curve
1	0.082	0.131	0.425	0	1.064	EPA
2	0.131	0.339	2.933	0	2.015	EPA
3	0.339	0.400	19.92	0	3.784	EPA
4	0.400	0.600	16.0	0	3.20	HB
5	0.600	1.250	9.6	0	2.010	HB
6	1.250	1.400	6.85	0	3.650	HB
7	1.400	1.600	5.9	0	4.300	HB

It is observed from Figure C-13 that the ISIS based rating curve matches well with the post-1984 spot flow measurements for the higher flow values except the largest spot flow. Even assuming the minimum roughness value and the maximum weir coefficient the post-1984 largest flow could not be matched although the other high flows were matched. With the low value of roughness coefficient and high value of spill, the low flows are slightly overestimated by the ISIS based rating curve. Therefore the proposed rating curve adopts the EPA rating for the low flow and the ISIS based rating for the high flow regime.

The median flow Q_{med} at Station 08009 Balheary on the Ward River is 5.77m^3/s from the EPA rating and 4.97m^3/s from the HB rating. The specific Q_{med} value (i.e., Q_{med} / $A^{0.77}$) at this station is only 0.207 m^3/s (HB rating), whereas the neighbouring Broadmeadow River (Station 08008 Broadmeadow) has specific Q_{med} value of 0.564m^3/s. All the annual maximum flow values at Station 08009 Balheary are smaller than 7.0m^3/s except the 12 June 1993 value which is 15.0m^3/s.

Further investigation of the annual maximum water levels at this station reveals that the annual maximum water levels of all years are within the baffle and the water level of 12 June 1993 is in-bank (see Figure C-14 below).

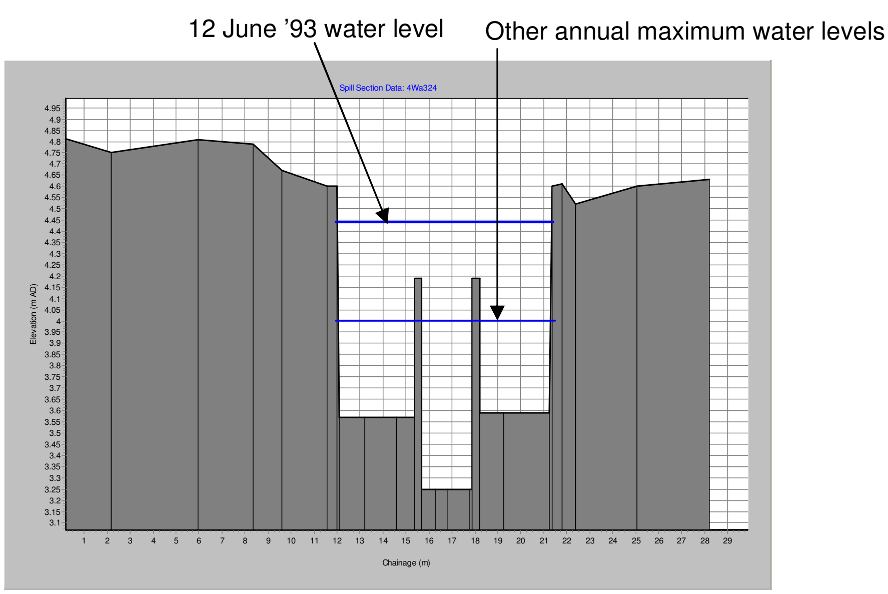


Figure C-14: Station 08009 Balheary (located just u/s of the fish-pass)

The instantaneous flow series available from the EPA for Station 08009 Balheary does not include the gauge height of the 26 August 1986 event (see Figure C-3 lower). The EPA have indicated that the gauge could have malfunctioned during extreme flood events.

C1.7 Station 080010 Garristown on the Garristown Stream

Hydrometric Station 08010 Garristown on the Garristown Stream is located on the right bank of the Garristown stream approximately 0.5km northeast of Garristown. According to the EPA, FCC constructed a channel control at Station 08010 in September 2002 to improve the quality of the rating curve. According to the EPA, a data logger has been installed at this weir on 18 November 2009. It is assumed that the old station was located at approximately the same location (see Figure C-15 below).

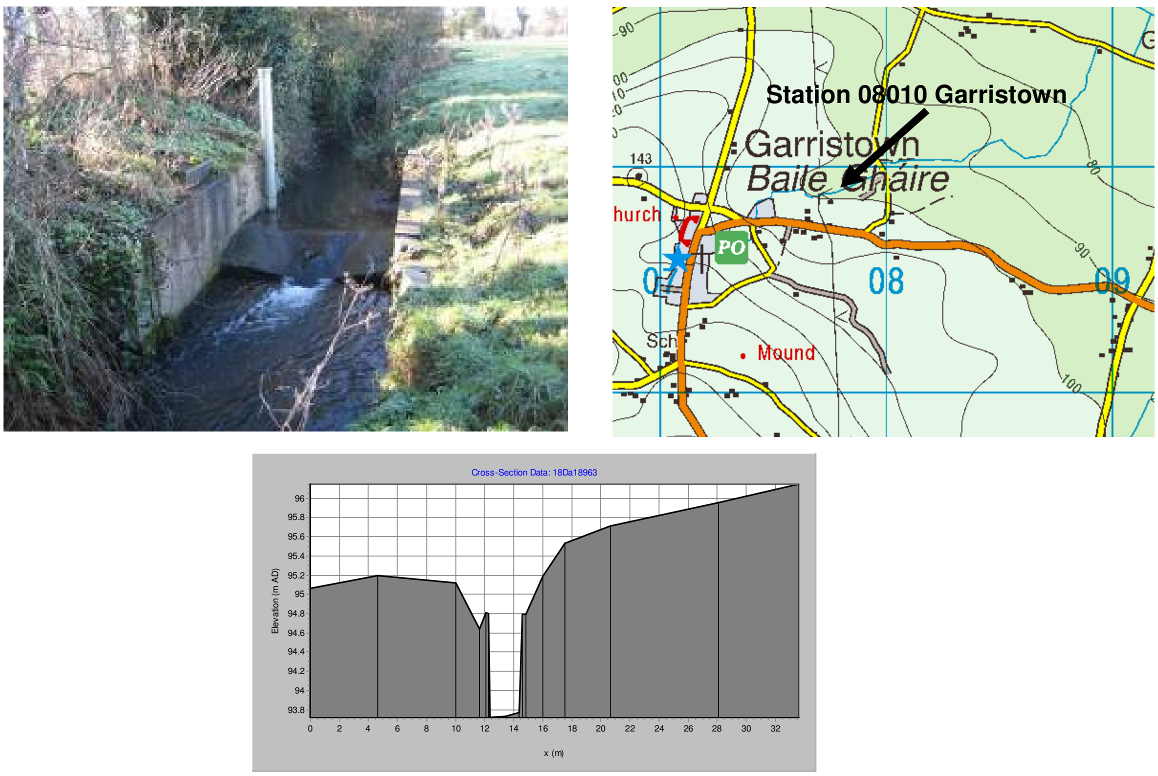


Figure C-15: Photo, location and channel cross section of Station 08010 Garristown

The ISIS river model is fitted with 11 river cross sections and one weir at the gauging station. The downstream boundary of the model consists of a normal depth boundary unit. The ISIS model was calibrated against gauged data with adjustments to the Manning's roughness coefficient and weir coefficient. The results of the rating reviewed and the revised rating are shown in Figure C-16 and Table C-7.

Table C-7: Parameters of the rating equation $Q(h) = C^*(h+a)^b$ for Station 08010 Garristown

Section	Minimum stage (m)	Maximum stage (m)	C	a	b	Rating curve
1	0.104	0.141	42.20	0.051	5.235	EPA
2	0.141	0.250	1.65	-0.037	2.390	EPA
3	0.250	0.300	2.700	-0.037	2.600	HB
4	0.300	0.350	2.600	0	2.740	HB
5	0.350	0.400	2.650	0	2.650	HB
6	0.400	0.600	2.44	0	2.50	HB
7	0.600	1.000	1.95	0	2.00	HB

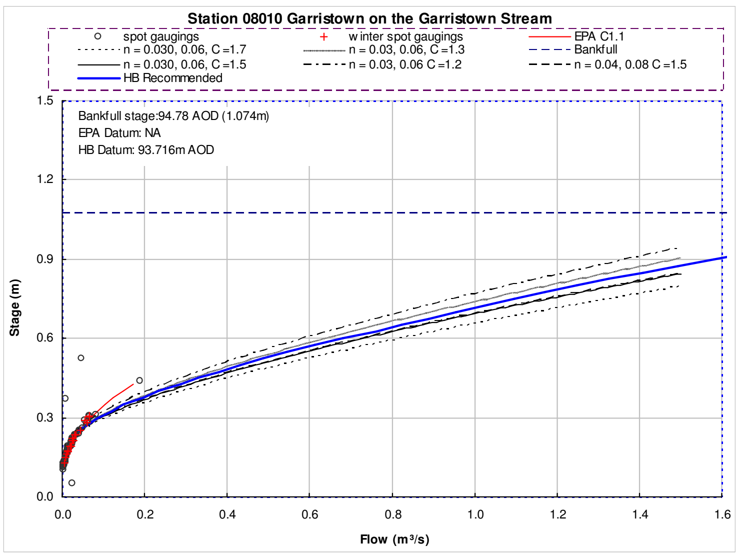


Figure C-16: Rating curve for Station 08010 Garristown on the Garristown Stream

It is observed from Figure C-16 that the spot flows were scattered but the rating curve matches most of the points. For the low flow regime the EPA rating is adopted as the ISIS based rating was slightly underestimating the low flow values. But for the high flow regime the ISIS based rating is adopted.

The hydrometric data at Station 08010 Garristown has been assigned with a TBM (temporary bench mark) datum of 98.826m. The EPA confirmed on 24th July 2009 that a true datum is not available at this station. The crest level of the newly constructed low flow weir is at 93.831 m OD Malin Head. However the ISIS based stage-discharge calibrated with the available spot levels matched by assuming the true datum as 93.716m OD, the lowest bed level of the channel section at GS 08010 Garristown. The EPA has been further requested to provide the true datum of the old Gauging Station.

The Q_{med} value from the EPA rating was 0.38m^3/s, however with the revised rating the Q_{med} value is 0.62m^3/s. With a catchment area of 1.13km^2, the specific Q_{med} is 0.564m^2/s, which is similar to the results from other hydrometric stations in the study catchment.

C1.8 Station 080011 Duleek on the Nanny River

Hydrometric Station 08011 Duleek on the Nanny River is one of the two stations installed by the OPW and still in operation in Hydrometric Area 08. The gauge is located on the left bank of the Nanny River just downstream of Duleek Bridge on R152. Duleek Bridge acts as a partial control for this gauging station (see Fig C-17 below).

The Nanny River has a wide flood plain both upstream and downstream of the gauging station. The Duleek area has experienced severe flooding in the past, two prominent floods occurred in 1986 and 2000. The Nanny River natural channel has a limited flow capacity and during the extreme flood events the river has large overbank flows.

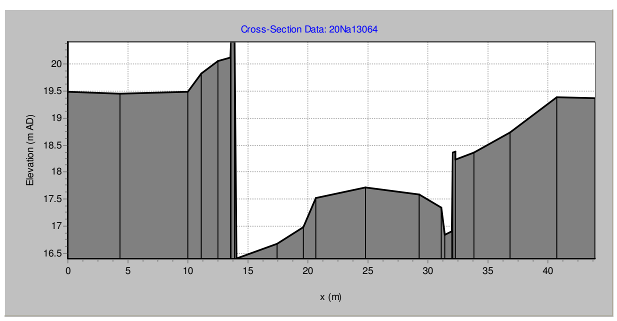


Figure C-17: Photo, location and channel cross section of Station 08011 Duleek

The ISIS river model is fitted with 18 river cross sections and one bridge. The downstream boundary of the model consists of a normal depth boundary unit. The ISIS model was calibrated against gauged data with adjustments to the Manning's roughness coefficient and weir coefficient. The ISIS model was fitted to match the OPW spot gauge measurements, using high value of Manning's n (for floodplain n = 0.09 to 0.12 and for in-bank, n = 0.035 to 0.04). The results of the rating reviewed and the revised rating are shown in Figure C-18 and Table C-8.

Table C-8: Parameters of the rating equation $Q(h) = C*(h+a)^b$ for Station 08011 Duleek

Section	Minimum stage (m)	Maximum stage (m)	C	a	b	Rating curve
1	0.0000	1.097	22.6	-0.56	2.24	OPW
2	1.0970	2.400	8.2	-0.32	1.50	OPW
3	2.400	3.500	2.85	-0.32	2.95	HB
4	3.500	4.000	2.31	-0.32	3.11	HB

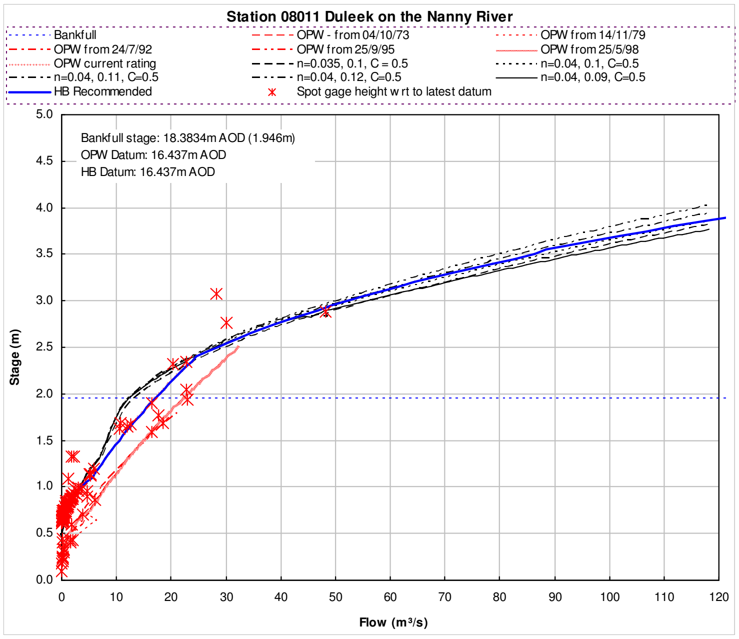


Figure C-18: Rating curve for Station 08011 Duleek on the Nanny River

The ISIS based rating matches with the high stage flows except the spot flow with the largest gauge height (at SG 3.07m, Q of 28.2m^3/s on 18/12/2000). The OPW was requested to confirm this spot flow, and it was confirmed by the OPW that this spot flow value is suspicious.

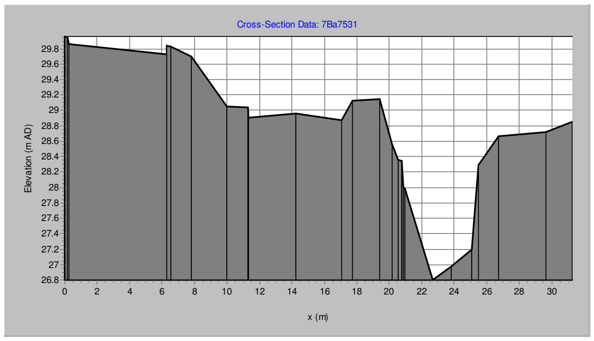
As the ISIS model was fitted for high stage flows, the OPW latest rating was adopted for gauge heights up to 2.4m, which is supported by several spot flows. However, for the stage beyond 2.4m height, the ISIS based rating is adopted.

The ISIS-1D model in the vicinity of the gauging station shows large volumes of floodplain flow in the vicinity of the gauging station and further downstream. The river appears to have insufficient flow capacity, thus during extreme flood events, there would be significant overbank flows.

For a gauge height larger than 2.4m, the Halcrow Barry proposed rating produced much higher value of AMS than the corresponding values of the OPW AMS. The Q_{med} value from the OPW AMS is 33.6m^3/s whereas that from the Halcrow Barry proposed rating is 48.4m^3/s. The Halcrow Barry rating based Q_{med} is approximately 44% higher than that of the OPW. The specific Q_{med} value from the OPW rating is 0.61m^3/s whereas that from the Halcrow Barry rating is 0.884m^3/s.

C1.9 Station 080012 Ballyboghill on the Ballyboghill River

Hydrometric Station 08012 Ballyboghill on the Ballyboghill River is located at downstream of the R108 Bridge at Ballyboghill. The gauge is located on a low weir, on the left bank of the Ballyboghill River and is easily accessible from the R129 (see Figure C-19).



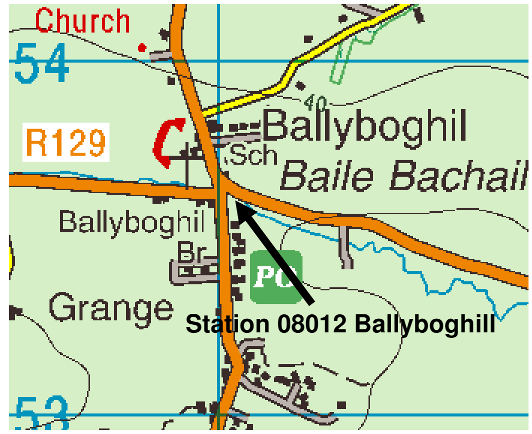


Figure C-19: Photo, location and channel cross section of Station 08012 Ballyboghill

The ISIS river model is fitted with 18 river cross sections, three structures and one weir at the gauging station. One structure at the most upstream end is modelled by ISIS orifice and spill unit, the bridges by ISIS bridge unit and spill unit and the weir by ISIS spill unit. The downstream boundary of the model consists of a normal depth boundary unit. The ISIS model is calibrated by adjusting the Manning's roughness coefficient and weir coefficient. The results of the rating reviewed and the revised rating are shown in Figure C-20 and Table C-9.

Table C-9: Parameters of the rating equation $Q(h) = C*(h+a)^b$ for Station 08012 Ballyboghill

Section	Minimum stage (m)	Maximum stage (m)	C	A	b	Rating curve
1	0.200	0.308	3956.7	-0.20	5.40	EPA
2	0.308	0.544	19.3	-0.20	3.01	EPA
3	0.544	1.000	3.700	-0.20	1.60	HB
4	1.000	1.500	4.200	-0.20	2.10	HB
5	1.500	1.700	3.450	-0.20	2.80	HB
6	1.700	2.000	2.450	-0.20	3.60	HB

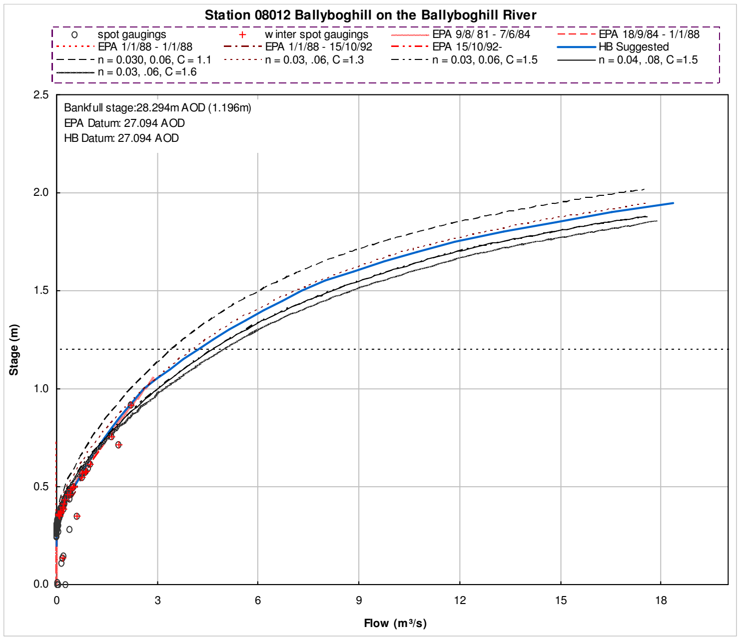


Figure C-20: Rating curve for Station 08012 Ballyboghill on the Ballyboghill River

It is observed from Figure C-20 that the ISIS based rating curve matches well with the median and higher values of spot flows.

The flow values of the Halcrow Barry rating based AMS are generally larger than the corresponding values of the EPA rating based AMS. The Q_{med} from the HB rating is 6.83 m^3/s compared with 5.0m^3/s from the EPA rating. Moreover, the specific Q_{med} from the HB rating is approximately 0.63m^3/s in comparison to 0.462m^3/s from the EPA rating. The Specific Q_{med} value at Ballyboghill is similar to those of other stations in the study area.

C2 Design flood estimates

C2.1 Station 08002 Naul on the Delvin River

A total of 23 annual maximum gauge heights were abstracted from the available hydrometric data received from the EPA. The November 2002 water level was taken from a separate EPA Report on the November 2002 flooding in the Delvin catchment. The modified AMS (24 values) was generated from the reviewed rating. The Q_{med} value from the AMS is 4.40m^3/s. For a catchment area of 37km^2, the specific Q_{med} (Q_{med} / CA$^{0.77}$) is 0.273m^3/s, which is slightly smaller than other stations in the study area except Station 08009.

The flood frequency curves from the at-site growth curve and the regional (study area) growth curve together with the 95% confidence intervals are presented in Figure C-21

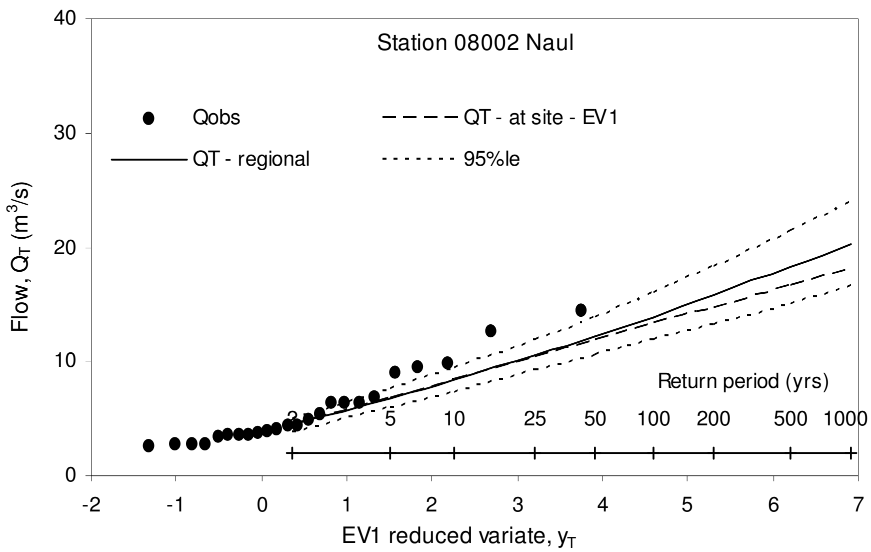


Figure C-21: Flood frequency curve and 95%le limit at Station 08002 Naul on the Delvin River

Figure C-21 shows the flood frequency curves from the regional (study area) growth curve (thick line), at-site growth curve (dashed line) and the 95% confidence interval. The regional growth curve based frequency curve is adopted for this station. The design flood of various return periods together with the 95%ile confidence limit is presented in Table C-10.

Table C-10: Design flood of various return period at Station 08002 Naul

T (years)	2	5	10	25	50	100	200	1000
Q_T (m^3/s)	4.4	6.7	8.3	10.5	12.2	13.9	15.7	20.3
95%le lower	3.9	5.9	7.3	9.1	10.5	11.8	13.2	16.7
95%le upper	4.9	7.5	9.4	11.8	13.8	16.0	18.3	23.8

It is observed from Figure C-21 and Table C-10 and that both the at-site (EV1 based) growth curve and the regional growth curve produce the 100-year flood values slightly smaller than largest value of AMS (14.47m^3/s) recorded in December 1978. However, this flood value lies within the 95% confidence limit of 100-year design flood, which is 16m^3/s.

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The November 2002 flood value (9.83m^3/s) and the August 1986 flood value (6.89m^3/s) are much smaller than the estimated 100-year flood values. It was noted that the EPA current rating was changed in June 1980. The pre-1980 EPA rating based value for the largest flood of December 1978 was 13.39m^3/s, which is slightly smaller than the design 100-year flood value.

C2.2 Station 08005 Kinsaley Hall on the Sluice River

A total of 23 annual maximum gauge heights were abstracted from the available hydrometric data received from the EPA. The modified AMS (23 values) was generated from the reviewed rating. The Q_{med} value is 3.17m^3/s and the specific Q_{med} (= Q_{med} / $CA^{0.77}$) is 0.534m^3/s.

Flood frequency curves from at-site and regional growth curves are presented in Figure C-22.

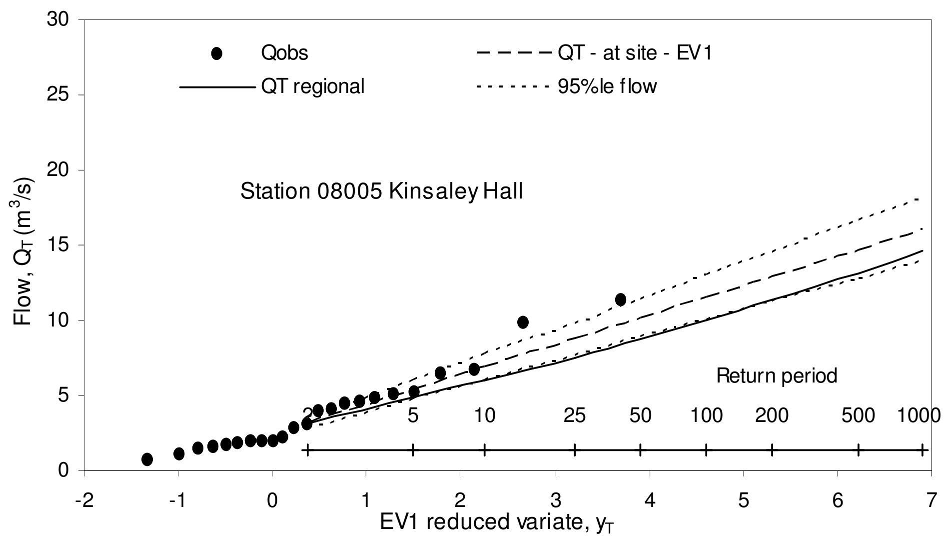

Figure C-22: Flood frequency curve and 95%le limit at Station 08005 Kinsaley Hall

It is observed from Figure C-22 that the 100-year return period flood value from the regional growth curve is lower than the largest flood value (11.4m^3/s) in the AMS. The largest flood value was recorded in the year 2000, which is the last recorded AMS value available at the gauging station.

The Sluice catchment area consists of more significant urbanization than most of the other catchment in the study area. Therefore, the regional growth curve for the predominantly rural study area may not be representative of this gauge (refer Section 9.2.2 of FEH Vol. 3 discussion on modifying regional growths for ungauged urban catchments).

Instead of modifying the regional growth curve at the Sluice catchment, it is recommended to use the at-site growth curve so as to incorporate the effects of urbanization in the catchment itself. The adopted design floods (EV1 distribution based at-site flows) and the 95% confidence intervals of the design floods are presented in Table C-11.

Table C-11: Design flood of various return period at Station 08005 Kinsaley Hall

T (years)	2	5	10	25	50	100	200	1000
Q_T (m^3/s)	3.2	5.4	6.9	8.7	10.1	11.5	12.9	16.0
95%le lower	2.8	4.8	6.0	7.7	8.8	10.0	11.2	13.9
95%le upper	3.5	6.0	7.7	9.8	11.4	13.0	14.5	18.1

It is observed from Table C-11 that the 100-year design flood value (11.5m^3/s) is higher than all the annual maximum flood values at the station.

C2.3 Station 08007 Ashbourne on the Broadmeadow River

A total of 20 annual maximum gauge heights were abstracted from the hydrometric data received from the EPA. The November 2002 water level was taken from a separate EPA Report on the November 2002 flooding in the Broadmeadow catchment. No records exist between 1997 and 2002.

The revised AMS (21 values) was generated from the reviewed rating. The Q_{med} value from the AMS is 8.16m^3/s. For a catchment area of 34km^2, the specific Q_{med} (Q_{med} / $CA^{0.77}$) is 0.54m^3/s.

Flood frequency curves from at-site and regional growth curves together with the 95% confidence interval are presented in Figure C-23.

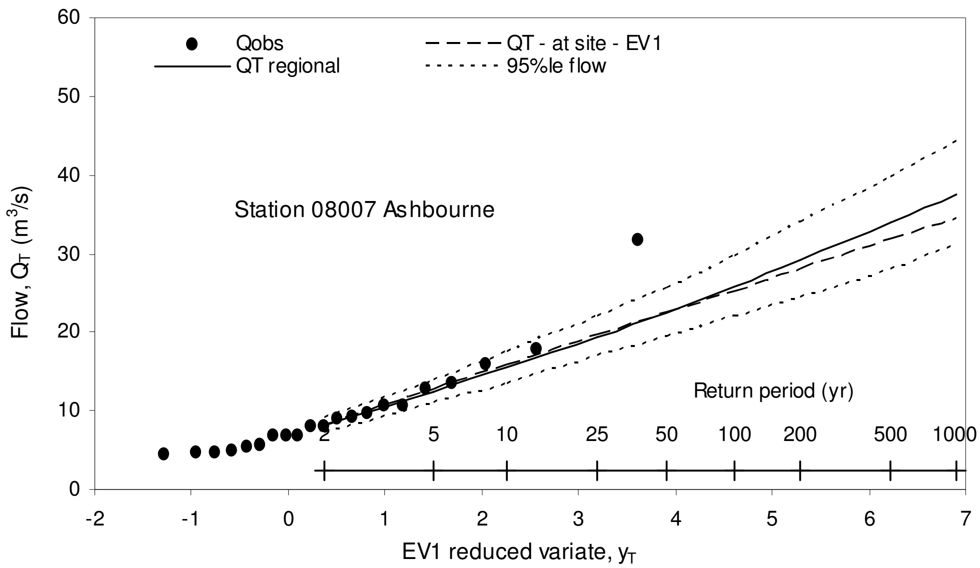

Figure C-23: Flood frequency curve and 95%le limit at Station 08007 Ashbourne on the Broadmeadow River

The study growth curve based frequency curve is adopted for this station, which produces the following design flood values at various return periods (Table C-12).

Table C-12: Design flood of various return period at Station 08007 Ashbourne

T (years)	2	5	10	25	50	100	200	1000
Q_T (m^3/s)	8.2	12.4	15.4	19.4	22.6	25.8	29.2	37.6
95%le lower	7.1	10.9	13.5	17.0	19.5	21.9	24.4	31.0
95%le upper	9.2	14.0	17.4	21.9	25.6	29.6	33.9	44.1

The largest AMS value of 31.8m^3/s (the 2002 flood estimate based on water marks) is larger than the design 100-year flood. The omission of records between 1997 and 2002 may have the effect of distorting the plotting position of the 2002 flood event (i.e. suggesting a lower return period). All other annual maximum flood values matching closely to the frequency curves and their values are lower than the 100-year design flood.

C2.4 Station 08008 Broadmeadow on the Broadmeadow River

A total of 28 annual maximum water levels were available at the OPW website www.opw.ie/hydro. The HB recommended rating produced lower values of AMSs at this station than those from the OPW rating. The Q_{med} value from the modified AMS 21.06m^3/s and specific Q_{med} (Q_{med} / $CA^{0.77}$) is 0.564m^3/s, which is quite close the specific Q_{med} value at Station 08007-Ashbourne on the Broadmeadow River.

Flood frequency curves of from the at-site growth curve and regional area growth curve together with the 95% confidence interval are presented in Figure C-24 below.

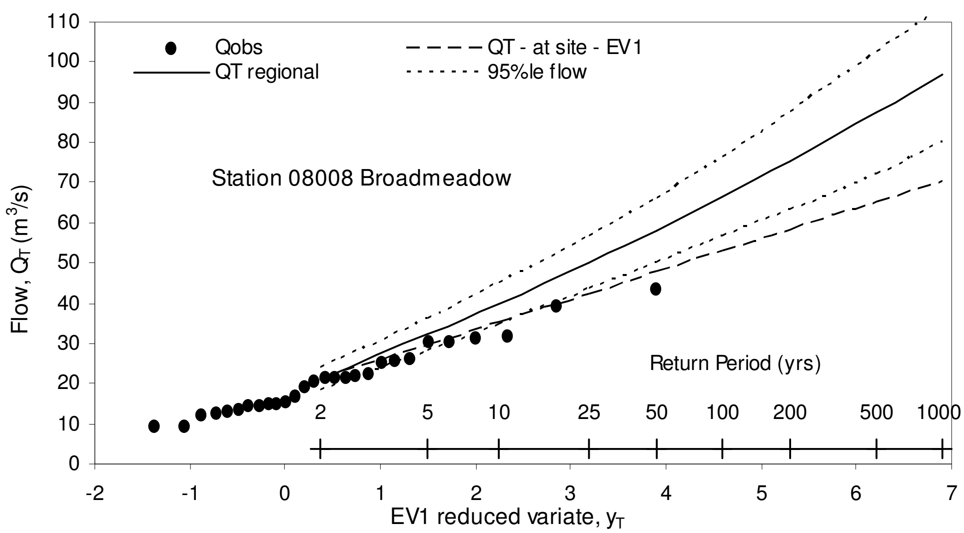

Figure C-24: Flood frequency curve and 95%le limit at Station 08008 Broadmeadow on the Broadmeadow River

It is observed from Figure C-24 that the frequency curve based on the at-site growth curve closely matches the annual maximum flood values. However, the at-site growth curve produces smaller peak flow values than the regional growth curve. The general approach adopted in the present study is to adopt the peak flood values based on the regional growth curve. The following design flood values of various return periods are produced from the regional growth curve (Table C-13).

Table C-13: Design flood of various return period at Station 08008 Broadmeadow

T (years)	2	5	10	25	50	100	200	1000
Q_T (m^3/s)	21.1	32.1	39.8	50.1	58.2	66.6	75.3	96.9
95%le lower	18.4	28.1	34.8	43.8	50.3	56.6	63.1	79.9
95%le upper	23.7	36.1	44.8	56.5	66.1	76.5	87.5	113.9

It is observed from Figure C-24 and Table C-13 that the 100-year return period design flood (66.6 m^3/s) is much larger than the highest value of Annual maximum flood (43.67m^3/s).

C2.5 Station 08009 Balheary on the Ward River

A total of 15 (1980 to 1995) annual maximum water levels were available from the EPA for Station 08009 Balheary. The HB suggested rating produced slightly lower values of modified AMSs than that from EPA rating. The Q_{med} value from the modified AMS is 4.97m^3/s. For a catchment area of 62km^2, this gives a specific Q_{med} (Q_{med} / $CA^{0.77}$) of only 0.207m^3/s. The specific Q_{med} value is extremely small with respect to the adjacent Broadmeadow catchment (0.564m^3/s) and the regional area median value of 0.545m^3/s. On the L-moment ratio diagram, the L-moment ratio of the Ward AMSs was located at the extreme upper right corner. The AMS of the Ward River was therefore excluded from the pooling group regional analysis.

To estimate the design flood at Ward, the modified specific Q_{med} of the study area i.e., 0.545m^3/s was adopted. For a catchment area of 62km^2, this gives a Q_{med} value of 13.07m^3/s. This Q_{med} was used together with the study area regional growth curve to estimate the design flood of various return periods.

The design flood of various return periods at Station 08009 Balheary are presented in Figure C-25 and shown on Table C-14.

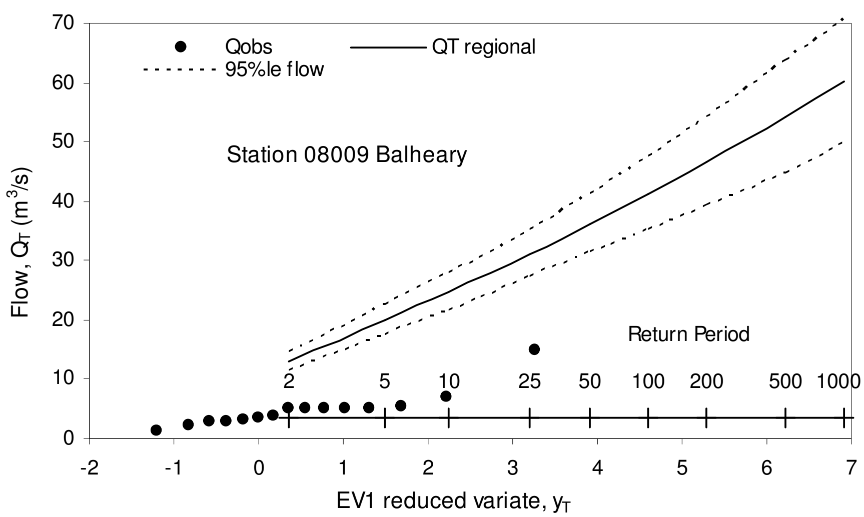

Figure C-25: Flood frequency curve and 95%le limit at Station 08009 Balheary on the Ward River

Table C-14: Design flood of various return period at Station 08009 Balheary

T (years)	2	5	10	25	50	100	200	1000
Q_T (m^3/s)	13.1	19.9	24.7	31.1	36.1	41.3	46.7	60.2
95%le lower	11.4	17.4	21.6	27.2	31.2	35.2	39.1	49.6
95%le upper	14.7	22.4	27.8	35.1	41.0	47.5	54.3	70.7

It is observed from Figure C-25 that all the annual maximum flood values are much lower than the recommended design peak flow of various return periods. The largest value of AMS in 1993 is equivalent to approximately the 2 to 5 year return period flood.

C2.6 Station 08010 Garristown on the Garristown Stream

A total of 13 annual maximum gauge heights were abstracted from the hydrometric data received from the EPA. The modified AMS was generated from the reviewed rating. The Q_{med} value from the modified AMS is 0.62m^3/s. For a catchment area of 1.13km^2, the specific Q_{med} (Q_{med} / $CA^{0.77}$) is 0.56m^3/s.

Flood frequency curves of from the at-site growth curve and regional growth curve together with the 95% confidence intervals are presented in Figure C-26 and Table C-15.

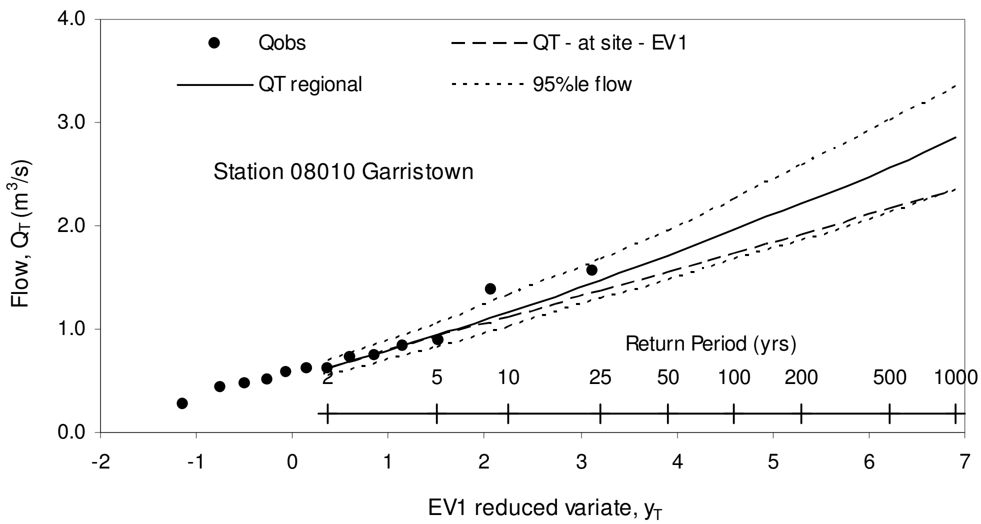

Figure C-26: Flood frequency curve and 95%le limit at Station 08010 Garristown on the Garristown Stream

Table C-15: Design flood of various return period at Station 08010 Garristown

T (years)	2	5	10	25	50	100	200	1000
Q_T (m^3/s)	0.62	0.94	1.17	1.48	1.71	1.96	2.22	2.85
95%le lower	0.54	0.83	1.03	1.29	1.48	1.67	1.86	2.35
95%le upper	0.70	1.06	1.32	1.66	1.95	2.25	2.58	3.35

It is observed from Figure C-26 and Table C-15 that the 100-year flood value of 1.96m^3/s is larger than highest value of AMS (1.57m^3/s).

C2.7 Station 08011 Duleek on the Nanny River

A total of 27 annual maximum water levels were available at the OPW website www.opw.ie/hydro for 1979 - 2006. One more annual maximum water level from 2007 was extracted from the series of water level available from the OPW. The HB recommended rating produced larger AMS values at this station. The Q_{med} value from the modified AMS is 48.4m^3/s in comparison to 33.6m^3/s from the OPW rating. The specific Q_{med} value from the modified AMS is 0.88m^3/s.

Flood frequency curves from at-site growth curve and regional area growth curve are presented in Figure C-27.

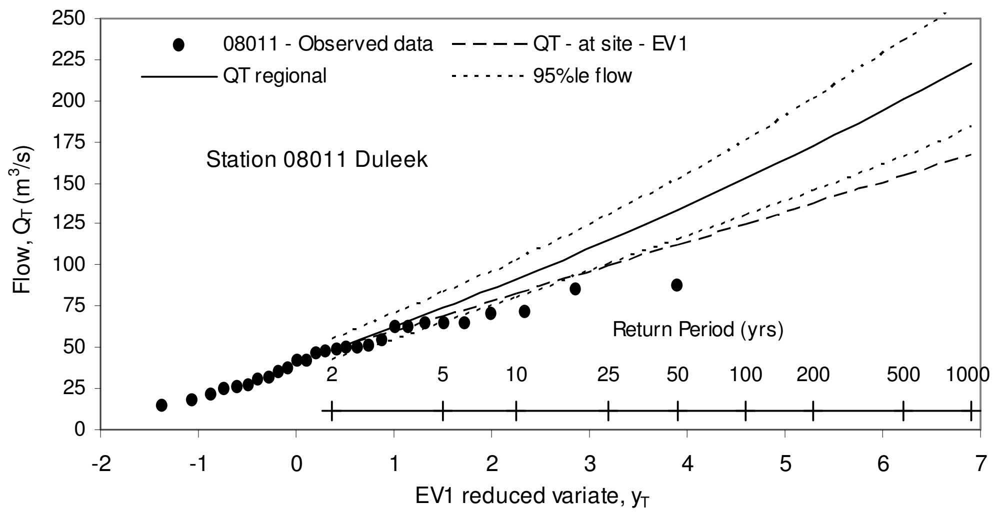

Figure C-27: Flood frequency curve and 95%le limit at Station 08011Duleek on the Nanny River

It is observed from Figure C-27 that the at-site growth curve based frequency curve matches closely with the annual maximum flood values. However, the at-site growth curve produces much smaller peak flow values than the regional growth curve at higher return periods. The general approach for the present study is to adopt the design flood values based on regional growth curve. The recommended design flood values of various return period and the 95%le confidence limits shown on Table C-16 are based on the regional growth curve.

Table C-16: Design flood of various return period at Station 08011 Duleek

T (years)	2	5	10	25	50	100	200	1000
Q_T (m^3/s)	48	74	91	115	134	153	173	223
95%le lower	42	65	80	101	115	130	145	184
95%le upper	54	83	103	130	152	176	201	262

C2.8 Station 08012 Ballyboghill on the Ballyboghill River

A total of 17 annual maximum gauge heights from 1980 to 1999 were abstracted from the hydrometric data received from the EPA for Station 08012. The modified annual maximum series was generated using the HB suggested rating curve. The Q_{med} value from the AMS is 6.83m^3/s in comparison to the EPA rating based AMS Q_{med} value of 5.02m^3/s. For a catchment area of 22.1km^2, the specific Q_{med} is calculated as 0.63m^3/s.

Flood frequency curves from at-site growth curve and regional growth curve together with the 95% confidence limits are shown on Figure C-28.

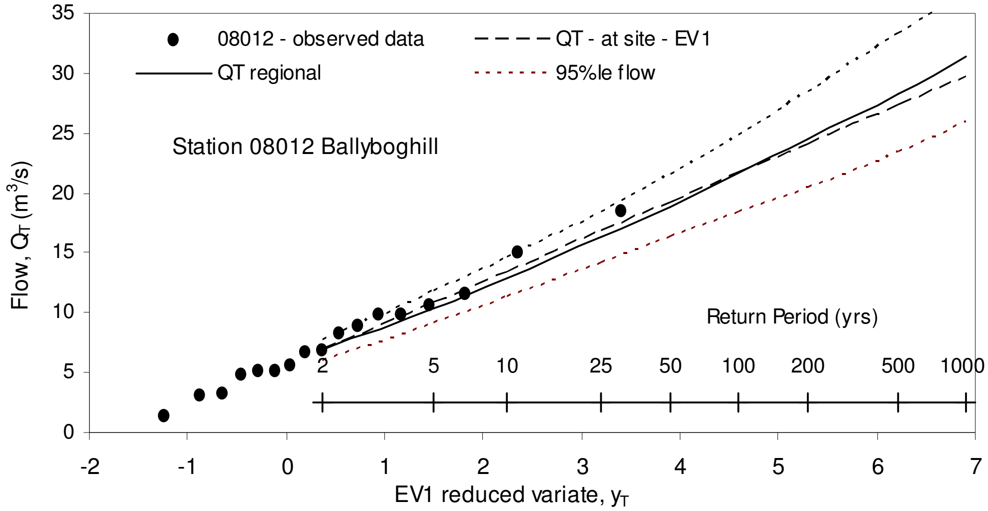

Figure C-28: Flood frequency curve and 95%le limit at Station 08012 Ballyboghill on the Ballyboghill River

It is observed from Figure C-28 that both frequency curves (from at-site and regional area growth curve) are quite similar. These curves are within the 95% percentile confidence limits. The two largest annual maximum flood values, which are slightly away from the two frequency curves, are also within the 95% confidence limits.

The suggested design floods of various return periods, based on regional growth curve, together with the 95%li flows are presented in Table C-17.

Table C-17: Design flood of various return period at Station 08012Ballyboghill

T (years)	2	5	10	25	50	100	200	1000
Q_T (m^3/s)	6.8	10.4	12.9	16.3	18.9	21.6	24.4	31.4
95%le lower	6.0	9.1	11.3	14.2	16.3	18.4	20.4	25.9
95%le upper	7.7	11.7	14.5	18.3	21.4	24.8	28.4	37.0

Appendix D: Future environmental and catchment changes

D1 Climate change – literature review

D1.1 Intergovernmental Panel on Climate Change (IPCC)

IPCC 4th Assessment report (2007)

The IPCC 4th Assessment report represents the culmination of the past six years of world wide scientific and technical literature published on climate change, its potential impacts and possible mitigation/adaptation options, at a global scale. The report states "Most of the observed increase in globally averaged temperatures since the mid-20th century is very likely (assessed likelihood >90%) due to the observed increase in anthropogenic greenhouse gas concentrations. For the next two decades a warming of about 0.2°C per decade is projected for a range of future greenhouse gas (GHG) emission scenarios. Even if the concentrations of all greenhouse gases and aerosols had been kept constant at year 2000 levels, a further warming of about 0.1°C per decade would be expected. A number of different scenarios are available to estimate what emissions might be expected in the future, encompassing a range of probable economic, political, population and technological developments in the next century. The best estimate of projected changes in mean global temperature for the end of this century range from 1.8 to 4°C, depending on the emissions scenario used.

It is very likely that heavy precipitation events will continue to become more frequent. Although there is no clear trend in the number of hurricanes occurring, some research suggests very intense storms are becoming more common as the oceans warm.

The report states that global average sea level rose at an average rate of 1.8mm/year (1961-2003) and this rate has accelerated to 3.1mm/year over the past decade (1993-2003). Although it is unclear whether the faster rate for 1993-2003 reflects decadal variability or an increase in the longer-term trend. Projections on globally averaged sea level rise by 2100 for various greenhouse gas emissions range between 0.18m to 0.38m (scenario B1: assuming a best estimate of 1.8°C increase) to between 0.26m to 0.59m (scenario A1FI: assuming a best estimate of 4.0°C increase).

The emission scenarios range from B1 with an emphasis on global solutions to economic, social and environmental sustainability, including improved equity, but without additional climate initiatives; to A1FI with an emphasis on increased cultural and social interactions, with a substantial reduction in regional differences in per capita income, with the energy system energy fossil intensive. These estimates are based on thermal expansion of ocean water and melting glaciers and ice caps. Beyond 2100, larger changes will occur due to the melting of ice sheets, having consequences on coastal communities and flooding.

Irish Committee on Climate Change – Ireland and the IPCC 4th Assessment Report (2007)

The Community Climate Change Consortium for Ireland (C4I) based at Met Éireann and the Irish Climate Analysis and Research Units (ICARUS) at NUI Maynooth have downscaled the latest climate models to project the impact of climate change in Ireland. The climate will potentially warm slightly faster than the global average over the next few decades, and winter rainfall will increase, predominantly in the west of Ireland. Summer rainfall will decline, predominantly on the east coast.

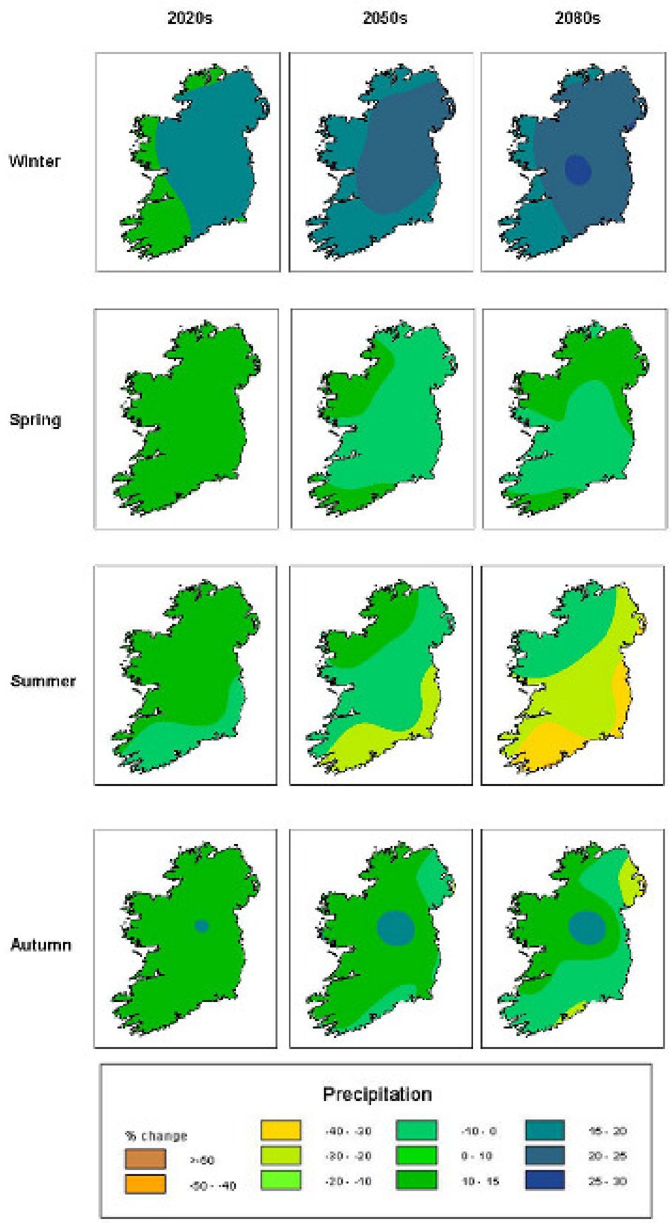

Figure D- 1: Percentage change in precipitation for Ireland from downscaling of global climate models. Source: Sweeny and Fealy, 2006.

Although summer precipitation in the east is expected to decrease, ICARUS state that "little change in winter precipitation is suggested as occurring on the east coast and in the eastern part of the Central Plain" (ICARUS website, Climate Change: Scenarios and Impacts for Ireland, accessed Jan '09).

However, an important consideration to bear in mind related to flood risk management is that the changes in precipitation projected by global and regional climate models are largely the result of changes in large-scale features in the atmosphere that exist across multiple grid cells within these models. Typically, these might be weather fronts bringing wide bands of rainfall across Ireland and the UK. Sub-grid scale processes, which include single or multi-cellular convective rainfall events, are not explicitly resolved in climate models currently (Dale, 2005).

This means that changes in intense convective rainfall events that are most common in the summer months (or between May and September) are not well captured by results that show an overall drying of the climate across Ireland and the UK during summer. Indeed, research indicates that such events are likely to increase in both their frequency and intensity in the future (Hulme et al, UKCIP Technical Report 2002). Such rainfall events can present extreme flooding problems in the maritime climate of Ireland and the UK, a recent example being the flooding at Boscastle in Cornwall in 2004.

D1.2 UK Climates Impact Programme 2002 (UKCIP, 2002)

UK

The UKCIP02 (Hulme *et al*, 2002) publication estimates climate change predictions for a range of parameters for four scenarios of future climate change, known as: High, Medium-high, Medium-Low and Low, relating to different greenhouse gas emissions scenarios. The future predictions are based on three time horizons, 2020, 2050 and 2080 (see Figures D-2 and D-3).

The findings estimate that UK winters will become wetter and summers drier. Extreme winter precipitation will become more frequent. As global temperature warms, global-average sea level may rise between 23cm and 36cm by the 2080's. Extreme sea levels, occurring through combinations of high tides, sea level rise and changes in wind will be experienced more frequently in many coastal locations (see Figure D-4).

Ireland

Although UKCIP does not deal with Ireland specifically, many of the graphical outputs contain Ireland.

For Ireland, winter precipitation totals are expected to increase and summer precipitation totals to decrease. This is a finding consistent with the Sweeney and Feeley 2006 report (see Figure D-1 above). However, graphical outputs from the UCKIP02 model suggest that under high emission scenarios winter precipitation on the east coast will increase by 20-25% for the climate period centred around 2080.

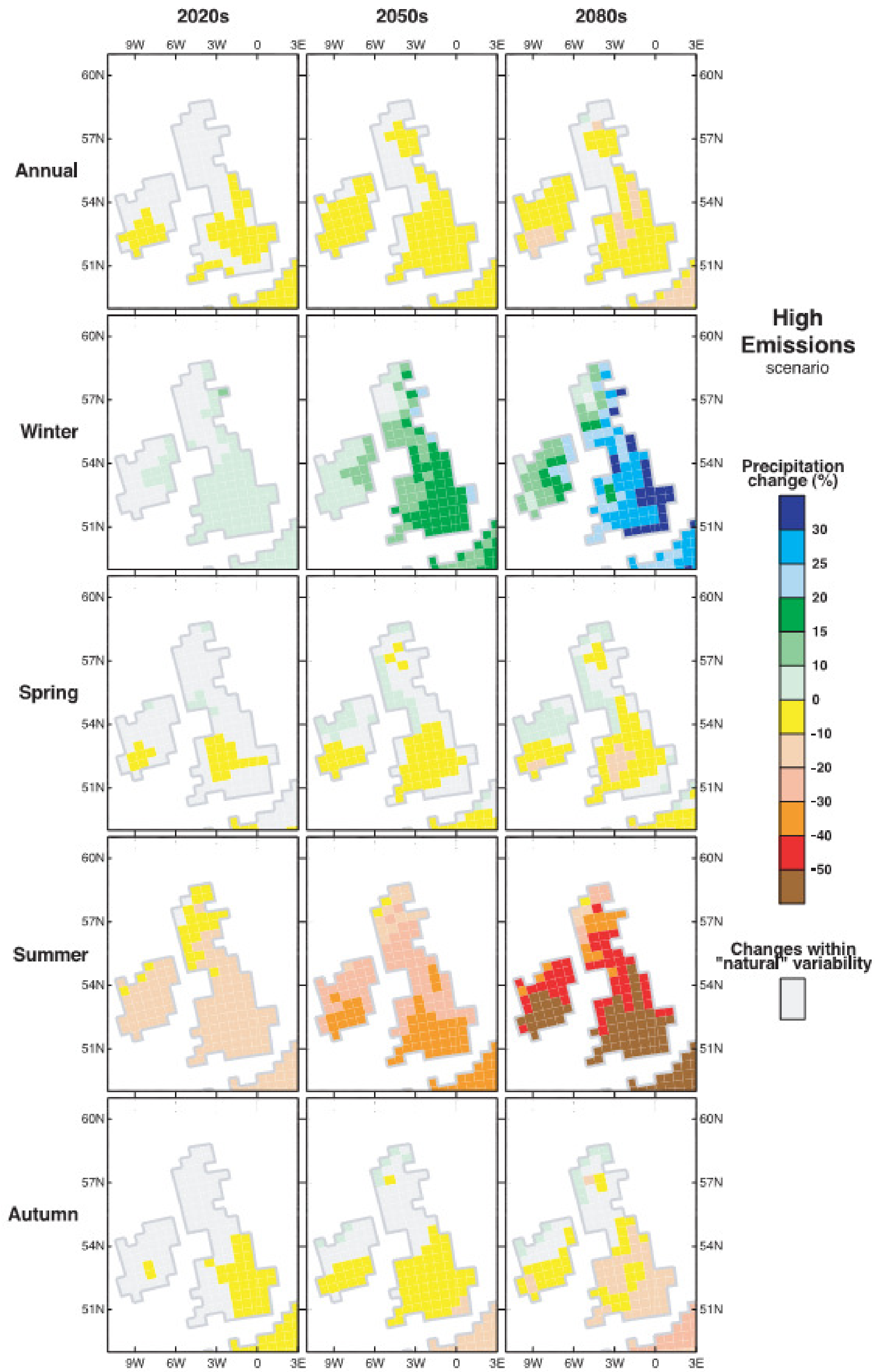

Figure D- 2: Percentage change in precipitation from UKCIP02 report using HadRM3 regional climate model. (Source: Hulme et al. The UKCIP02 Scientific Report, 2002)

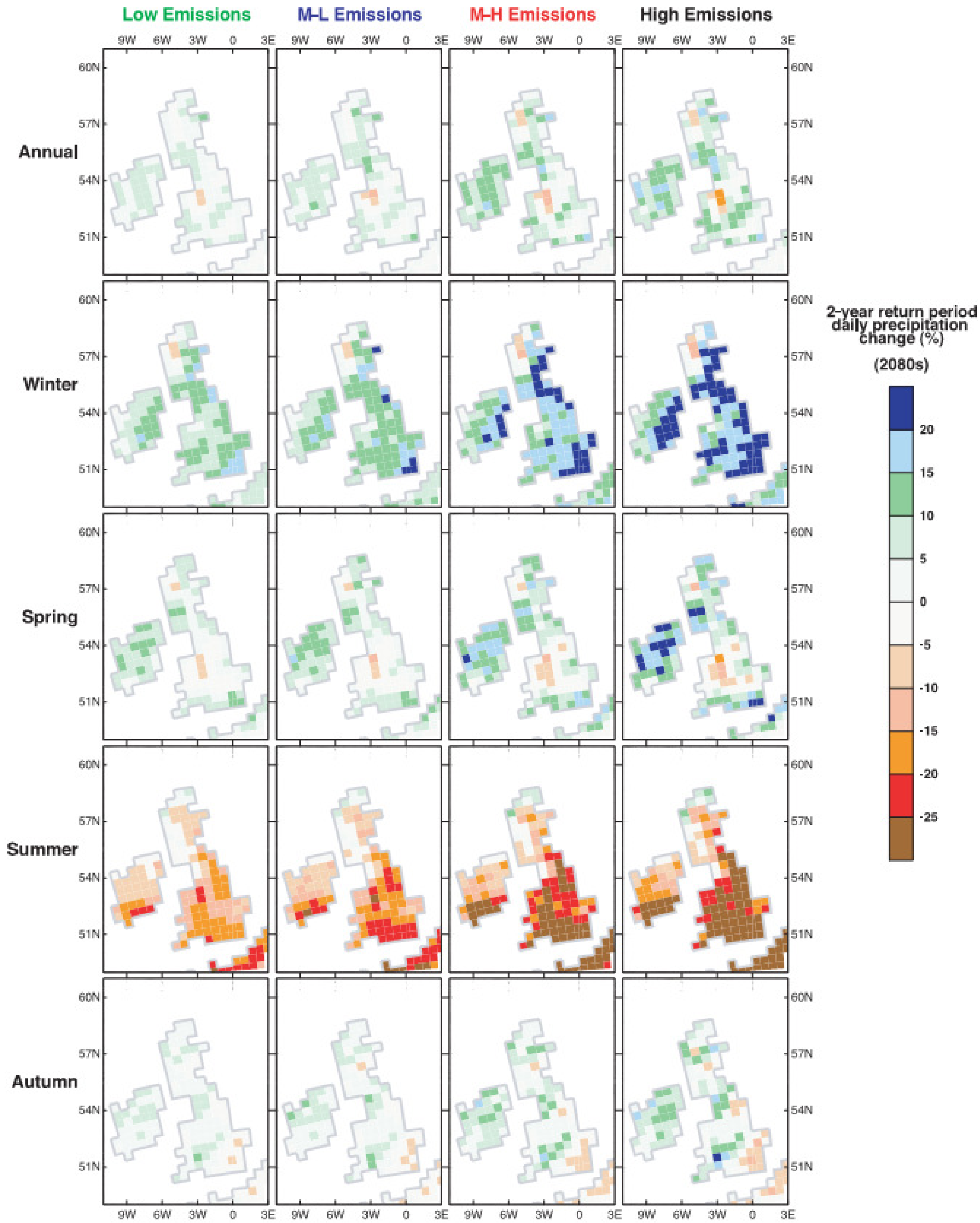

Figure D-3: Percentage change in precipitation for the 2-year return period event from UKCIP02 report using HadRM3 regional climate model. (Source: Hulme et al. The UKCIP02 Scientific Report, 2002)

Furthermore, in the UCKIP02 analysis of daily precipitation change, eastern Ireland shows increase by 20-25% of the 2-year return period event in the Medium-high and High emission scenarios. The UKCIP02 report states that, 'The large-scale patterns and percentage changes in amount are generally repeated for all return periods up to the number of years of available data."

Changes in global average sea level will occur as a consequence of global temperature change. The increase in sea level will be due to thermal expansion of ocean water and through melting of glaciers. It is estimated that global average sea level will rise by between 23cm and 36cm by 2080 depending on which emissions scenario is adopted.

The change in the 50-year return period surge height for the 2080s for the Irish sea adjacent to the study area for three different emissions scenarios is estimated to be 0.1-0.2m (Low emissions scenario), 0.3-0.4m (Medium-High emissions scenario) and 0.7-0.8m (High emissions scenario). This considers the combined effect of global-average sea-level rise, storminess changes and vertical land movements.

Sea-level rise will lead to locally deeper water in the near-shore zone and therefore lead to greater wave energy being transmitted to the shoreline. In addition changes in wind speed will also occur. The 2-year return period daily-average wind speed is estimated to increase by up to 6% for winter in the 2080s, assuming a Medium-high or High emissions scenario.

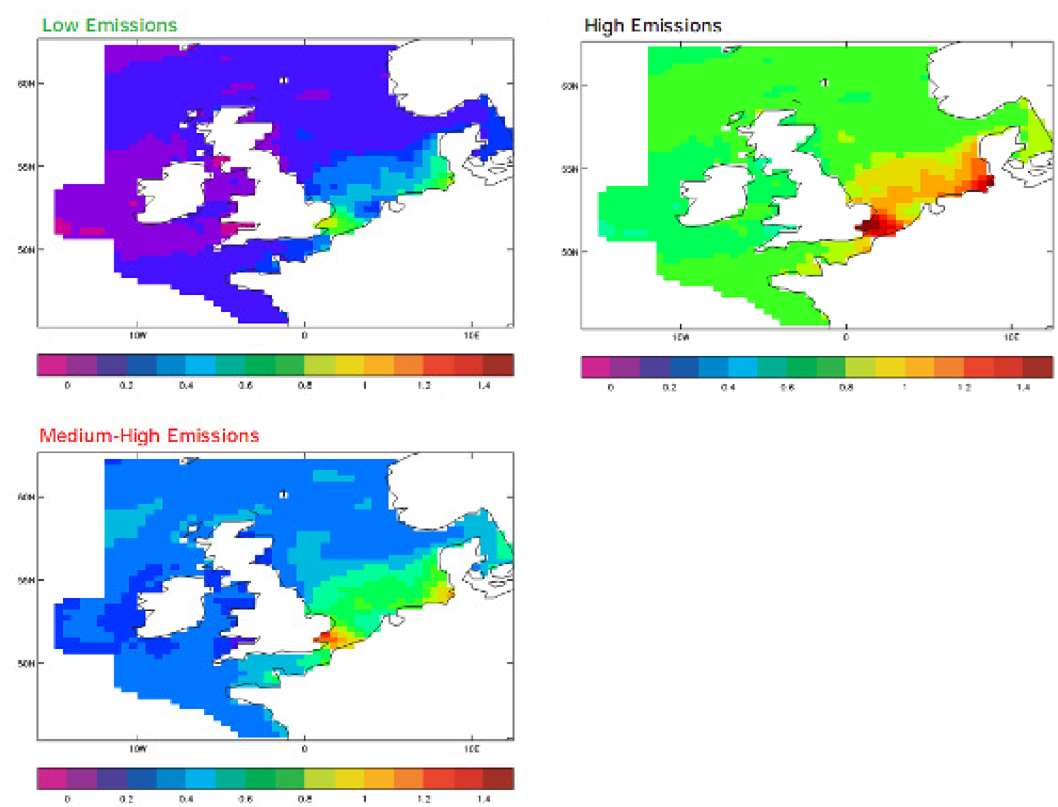

Figure D-4: Increase in 50-year surge height (m) for 2080 for different scenarios from UCKIP02 report. Includes effect of sea-level rise, storminess and vertical land movements. Sea-level rise estimates of 9, 30 and 69cm for low, medium and high scenarios respectively. (Source: Hulme et al. The UKCIP02 Scientific Report, 2002)

D1.3 Implications of the EU Climate Protection Target for Ireland (EPA, 2007)

The European Union (EU) has adopted a long-term climate protection target to limit global mean temperatures to not more than 2℃ above pre-industrial levels. This action is in response to the United Nations Framework Convention on Climate Change (UNFCCC) Article 2 objective which is to stabilise “greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system”.

The aim of the recent EPA published report by ICARUS (McElwain and Sweeney, 2007), was to provide an assessment of what the EU 2℃ target means for Ireland. Scientific analyses suggest that the rate of temperature increase may be as important as the absolute change. The current rate of global temperature increase of 0.2-0.3℃ per decade is already greater than that experienced over the past 10,000 years. A high rate of change can increase the risk of high-impact events.

McElwain and Sweeney, highlight that “Ireland will also experience significant climate change impacts below 2℃, many of which are now unavoidable. Adaptation actions will be required to reduce adverse impacts of these changes.” Increased frequency and magnitude of flooding will be a consequence of increasing global mean temperatures, which will have important implications for infrastructure and development on affected flood plains. There will also be impacts on the reliability of existing flood defences, and, in the future, increased insurance costs.

Predictions for future storms are still uncertain; however the theory supporting the drivers for hurricanes strongly suggests that peak intensities would be higher with warmer ocean temperatures.

Statistical downscaling from an ensemble of three Global Climate Models (GCM), project for the end of the present century (2080), an increase in precipitation of between 11% and 17% for winter months (Sweeney and Fealy, 2006).

Climate change impacts can occur in two ways; firstly, linear and smooth, thus relatively predictable, allowing society time to adapt and allowing impacts to be managed. Secondly, abruptly, occurring over timescales from years to decades, with little warning and leaving less time for adaptability.

D1.4 Regional Climate Model Predictions for Ireland (McGrath et al, 2005)

The Community Climate Change Consortium for Ireland (C4I) project has enabled the establishment of a regional climate modelling facility in Met Éireann, as documented in the C4I Annual Report 2004 (McGrath et al, 2004). A key objective is to develop a new national capacity to forecast future climate conditions in Ireland. This is considered to be necessary for the development of national planning for adaptation to the impacts of projected climate change.

McGrath *et al* (2005), provides an analysis of future Irish climate conditions for the period 2021–2060 based on the outputs from the Met Éireann Regional Climate Model (RCM) using 1961-2000 as a reference. The Met Éireann RCM improves the understanding of climate change and its implications for Ireland, and quantifies the uncertainties in the climate projections. It is based on the (SRES)-B2 scenario. Downscaled from the German global model ECHAM4 (from the Max Plank Institute).

The RCM projects temperature changes, which show a general warming in the future period with mean monthly temperatures increasing typically between 1.25 and 1.5℃, the largest increases are seen in the southeast and east, with the greatest warming occurring in July.

For precipitation, the most significant changes occur in the months of June and December; June values show a decrease of about 10% compared with the current climate, noticeably in the southern half of the country; March, July and August are largely unchanged but all other months show overall increases. December values show increases ranging between 10% in the south-east and 25% in the north-west. The area around Fingal and East Meath shows around 10% increase in monthly rainfall total in December. There is also some evidence of an increase in the frequency of extreme precipitation events (i.e. events which exceed 20 mm or more per day) in the north-west. Again, this is largely consistent with the findings of the UKCIP02 report, showing an overall drying in summer and wetter winters. The comments in section D1.1 regarding sub-grid scale changes in rainfall (intense convective events) should be borne in mind when considering this finding.

In the future scenario, the frequency of intense cyclones (storms) over the North Atlantic area in the vicinity of Ireland is increased by about 15% compared with the current climate, with even stronger increases in winter and spring. This is related to the projected general rise in sea surface temperatures.

The impact of climate change predictions on river flooding was modelled under different scenarios using the Suir catchment as a pilot study. The increase in winter precipitation was found to produce a significant increase in the more intense discharge episodes, raising the risk of future flooding in the area. The model predicts an increase in frequency and intensity of heavy discharges e.g. above $350m^3/s$. The 10 year return period flow increased from $290m^3/s$ to $360m^3/s$ (an increase of 24%). This highlights the implications faced by future planning to reduce impacts of flooding. It should be noted that the catchment response to rainfall is catchment specific and this will vary catchment to catchment.

D1.5 Scenarios and Impacts for Ireland (Sweeney et al, 2003)

This report presents an assessment of the magnitude and likely impacts of climate change in Ireland over the course of the current century, based on statistical downscaling of the GCM output from the Hadley Centre model (used in the UKCIP02 study), to project likely changes in Irish climate from the 1961–1990 averages. The results of this analysis suggest that current mean January temperatures in Ireland are predicted to increase by 1.5℃ by mid-century with a further increase of 0.5–1.0℃ by 2075. They predict that by 2055 the extreme south and south-west coasts have a mean January temperature of 7.5–8.0℃. It is predicted that by then, winter conditions in Northern Ireland and in the north Midlands will be similar to those currently experienced along the south coast. Since temperature is a primary meteorological parameter, secondary parameters such as frost frequency and growing season length and thermal efficiency can be expected to undergo considerable changes over this time interval. July mean temperatures are predicted to increase by 2.5℃ by 2055 and a further increase of 1.0℃ by 2075. Mean maximum July temperatures in the order of 22.5℃ will prevail generally with areas in the central Midlands experiencing mean maxima up to 24.5℃. Overall increases of 11% in precipitation are predicted for the winter months of December–February. The greatest increases are suggested for the north-west, where increases of approximately 20% are suggested by mid-century. Little change is indicated for the east coast and in the eastern part of the Central Plain.

Marked decreases in rainfall during the summer and early autumn months across eastern and central Ireland are predicted. Nationally, these are of the order of 25% with decreases of over

40% in some parts of the east. For the area of the Fingal and East Meath in the east, runoff is projected to decrease by up to 25% (Figure D-5). However, these decreases represent changes in large-scale rainfall features rather than sub-grid scale processes. As detailed in section D1.1, increases in the frequency and intensity of single or multi-cellular convective storms are predicted in the summer period, in contrast to the overall reduction in summer rainfall and runoff described in this and other reports.

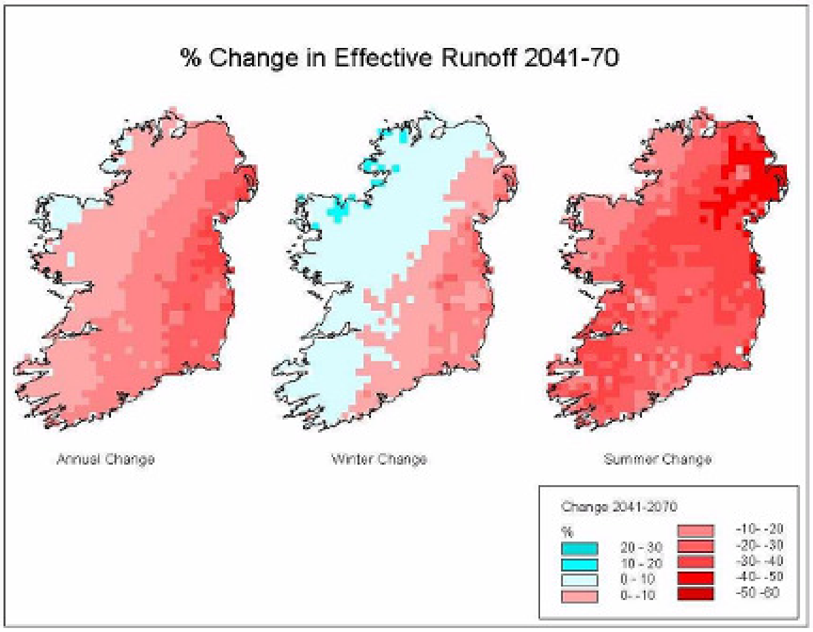

Figure D-5: Simulated change for 2041-2070 as a difference from the 1961-1990 baseline. (Source: Sweeny et al, 2003)

Global sea level is projected to rise by approximately 0.5m by the end of the century, predominantly due to warming and expansion of the ocean water body. In Ireland, this figure will be modified by local land-level changes.

As a general approximation, land retreat of about 1m can be anticipated on sandy coastlines in Ireland for every centimetre rise in sea level. Inundation risk must also take into account storm surge events and high tide frequencies. A value of 2.6m OD Malin for extreme water level presently occurs with a return frequency of 12 years on the west coast and 100 years on the east coast. These return periods of extreme water level are likely to reduce considerably as sea levels rise. Combining these extreme water levels with a sea-level rise of 0.49m places approximately 300km^2 of land in Ireland at risk of inundation.

In situations where land loss cannot be economically defended, it should not be contemplated. Where infrastructure is at risk of inundation, cost-beneficial solutions may exist. This is particularly the case in the cities of Dublin, Cork, Limerick and Galway, and for assets such as railway lines, airports and power stations.

D1.6 Foresight (2004)

The Foresight study, undertaken for the UK Office of Science and Technology (2004) provided a vision for flood and coastal defence in the UK between 2030 and 2100, to inform long-term policy. The study considered four scenarios based on different approaches to governance (centralised versus localised) and different values held by society (consumerist versus community). Various future drivers of flood risk were evaluated, including precipitation, relative sea level rise and surges. It was concluded that climate change has a high impact in all of the four scenarios studied. Relative sea level rise could increase the risk of coastal flooding by 4 to 10 times by 2080. Therefore, there could be a change in the frequency of flooding, for example a flood with a current Annual Exceedence Probability (AEP) of 1% could occur with an AEP of between 4% and 10% by 2080. Precipitation changes were predicted to increase risks across the country by 2 to 4 times by 2080, although specific locations could experience changes well outside this range. In addition, the increase in surge could increase the risk of coastal flooding by 2 to 10 times (depending on scenario adopted). [Risk is taken to mean: probability x consequences, where consequences relate to people and the natural and built environment].

D1.7 Projecting future sea level rise (Rahmstorf, 2007)

Due to the complex mechanisms and varying timescales involved, Rahmstorf used a semi-empirical model of sea-level rise, where a simple linear relationship is developed between observed global sea-level and observed temperature. Therefore, these estimates only consider eustatic (mean sea level) changes and do not take into account any storm surge component. This is done for the period 1880-2001, which reveals a highly significant correlation with an average rise of 3.4 mm per year. This relationship allows future sea-levels to be explored, given different scenarios of 21st century temperature. Using the IPCC Third Assessment Report future temperature scenarios (which span a range of temperature increases from 1.4 to 5.8℃) a eustatic sea-level rise of between 55 to 125cm by 2100 is estimated. These numbers are significantly higher than the model-based estimates of the IPCC, which give a range of 9 to 88cm for the same scenarios, and may have important implications for planning adaptation measures at the coast. Although such an approach makes the assumption that the observed relationship between global temperatures and global sea-level will hold in to the future, it does at least allow a lowest plausible limit to sea-level rise to be estimated. This is found to be 38 cm from 1990 to 2100, as any lower value would require that the rate of sea-level drops despite rising temperatures, an inverse of the pattern observed during the 20th century. It is important to appreciate that the values quoted here do not, as far as our understanding of the research goes, incorporate allowances for storm surge. Storm surge can result in temporary further increases in the sea level locally. Therefore, under certain meteorological conditions, use of these values could under-estimate actual sea levels in the future.

D1.8 Ireland in a warmer world: Scientific Predictions of the Irish Climate in the Twenty-First Century (McGrath and Lynch, C4I, June 2008)

This report is part of the C4I project run by Met Éireann. It reviews the computer simulations of Met Éireann and from the UCD Meteorology and Climate Centre from a regional climate model. The review covers storm surges, storminess, sea-level, and the impacts on hydrology in nine catchments.

Storm Surges (Chapter 3): Global data were downscaled onto a finer grid and the Regional Ocean Model System (ROMS) of Rutgers University was used to produce surge data. The results showed an increase in the frequency of storm surge events around the Irish coastal areas with the strongest increases in the northwest. There was also significant increase in surge height along the west coast. The 99 percentile change in surge height for Dublin Bay was 5.45% with a 5.6% change in maximum surge height and a 15% increase in surge frequency for surges between 50 and 100cm.

Sea-level (Chapter 6): The report states that satellite measurements show that sea levels are rising on average about 3.5cm per decade around Ireland. This is well in excess of any isostatic adjustment of the land level. This trend is set to continue with rising sea temperatures (causing thermal expansion of the water column). Changes in sea surface height measure by satellite altimetry put the trend for the Irish Sea at 2.7mm/year.

Hydrology (Chapter 7): A study of nine Irish catchments was carried out to investigate the impacts of climate change on hydrology in Ireland. Results for global climate models were downscaled using a regional climate model (under the scenario SRES-A1B and for the period 2021-2060) and used in a conceptual rainfall runoff model (HBV-Light). An amplification of the seasonal cycle was found across the country- with lower summer flow and higher winter flow. Elevated risk of flooding from increased precipitation events is particularly significant in the southwest of the country and for those catchments with fast response times. This research differs from that done on the Suir catchment as it uses Monte Carlo techniques (probabilistic approach) to calibration. Also significant bias was identified and removed from downscaled precipitation data.

Changes in the mean daily flow are positive for winter and negative for summer. For the Boyne catchment winter increases in mean daily flow of up to 20% could be expected. However, annual maximum mean daily flows were compared and for the Boyne catchment-only flows with current return periods of less than 20 years an increased risk is expected. For five of the nine catchments investigated, no change was expected in the severity of extreme events. The results are shown in Figure D-6. Again, it should be borne in mind that these results reflect the projected changes in rainfall resulting from large-scale features that can be simulated in climate models. Reductions in mean daily flow in summer, may be less marked than shown in the results due to localized convective rainfall events, whose intensity and frequency is predicted to increase in the future (discussed in Section D1.1).

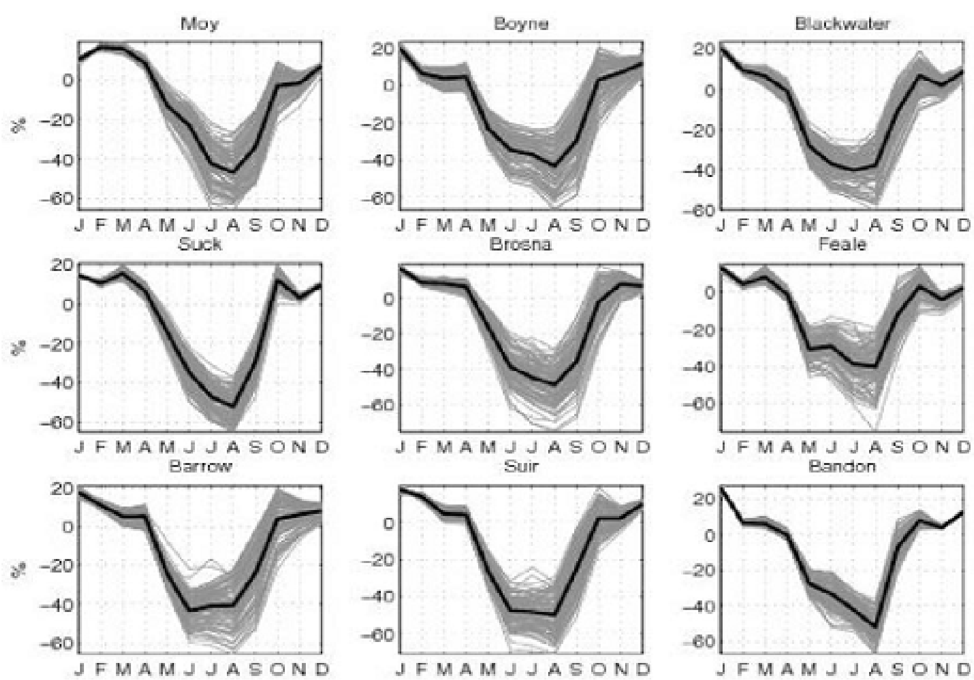

Figure D-6: Change in monthly mean daily flow due to climate change under SRES A1B scenario (2021-2060). (Source: Ireland in a Warmer World, 2008