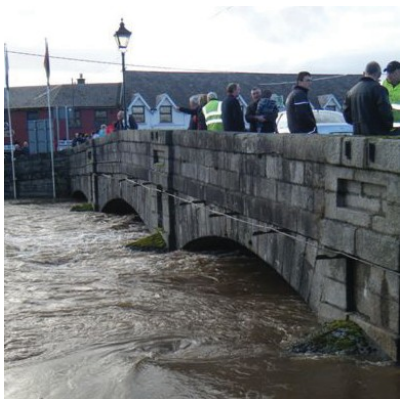
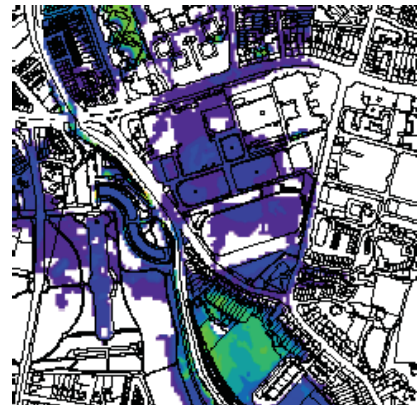
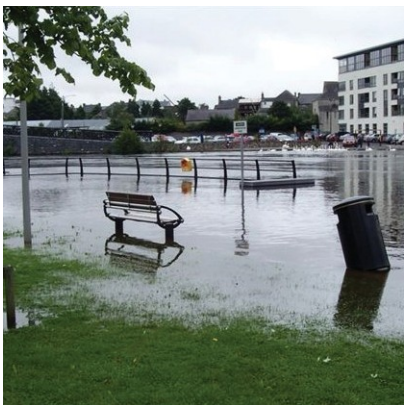
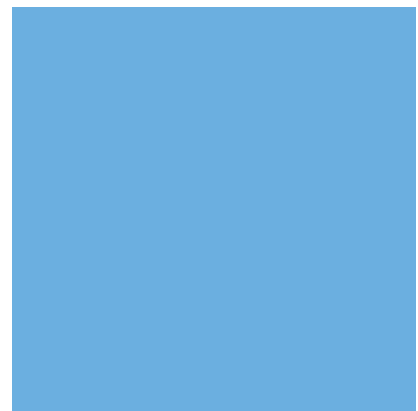




# South Eastern CFRAM Study

## HA 17 Hydrology Report

IBE0601Rp0013







# South Eastern CFRAM Study

## HA17 Hydrology Report DOCUMENT CONTROL SHEET

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## **APPENDICES**

**APPENDIX A   HA17 Hydrometric Data Status Table**

**1 Page**

**APPENDIX B   Design Flows for Modelling Input**

**14 Pages**

## ABBREVIATIONS

AEP	Annual Exceedance Probability
AFA	Area for Further Assessment
AFF	At-site Flood Frequency
AMAX	Annual Maximum flood series
AREA	Catchment Area
BFI	Base Flow Index
CFRAM	Catchment Flood Risk Assessment and Management
C4i	Community Climate Change Consortium for Ireland
CORINE	Coordination of Information on the Environment
CSO	Central Statistics Office of Ireland
DTM	Digital Terrain Model
ERBD	Eastern River Basin District
EV1	Extreme Value Type 1 (distribution) (=Gumbel distribution)
EPA	Environmental Protection Agency
FARL	Flood Attenuation for Rivers and Lakes
FEH	Flood Estimation Handbook
FEM-FRAMS	Fingal East Meath Catchment Flood Risk Assessment and Management Study
FRA	Flood Risk Assessment
FRMP	Flood Risk Management Plan
FSR	Flood Studies Report
FSSR 16	Flood Studies Supplementary Report No. 16
FSU	Flood Studies Update
GC	Growth Curve
GEV	Generalised Extreme Value (distribution)
GLO	General Logistic (distribution)
GSI	Geological Survey of Ireland
HA	Hydrometric Area
HEFS	High End Future Scenario (Climate Change)
HEP	Hydrological Estimation Point

HPW	High Priority Watercourse
HWA	Hydrograph Width Analysis
IH124	Institute of Hydrology Report No. 124
IPCC	Intergovernmental Panel on Climate Change
LA	Local Authority
LN2	2 Parameter Log Normal (distribution)
L-CV	Coefficient of L variation
MPW	Medium Priority Watercourse
MRFS	Mid Range Future Scenario (Climate Change)
NDTM	National Digital Terrain Model
OD	Ordnance Datum
OPW	Office of Public Works
OSi	Ordnance Survey Ireland
PFRA	Preliminary Flood Risk Assessment
$Q_{med}$	median of AMAX flood series
$Q_{bar} / QBAR$	mean average of AMAX flood series
RBD	River Basin District
RFF	Regional Flood Frequency
ROI	Region of Influence
SAAR	Standard Average Annual Rainfall (mm)
SERBD	South Eastern River Basin District
SuDS	Sustainable Urban Drainage
UAF	Urban Adjustment Factor
UoM	Unit of Management

# 1 INTRODUCTION

The Office of Public Works (OPW) commissioned RPS to undertake the South Eastern Catchment Flood Risk Assessment and Management Study (South Eastern CFRAM Study) in July 2011. The South Eastern CFRAM Study was the third catchment flood risk management study to be commissioned in Ireland under the EC Directive on the Assessment and Management of Flood Risks 2007 as implemented in Ireland by SI 122 of 2010 European Communities (Assessment and Management of Flood Risks) Regulations 2010.

The South Eastern CFRAM Study covers an area of approximately 12,857 km<sup>2</sup> and includes six Units of Management / Hydrometric Areas (Unit of Management Boundaries match the Hydrometric Area boundaries within the SECFRAM Study area). These are HA/UoM 11 (Owenavorrhagh), HA/UoM 12 (Slaney and Wexford Harbour), HA/UoM 13 (Ballyteigue - Bannow), HA/UoM 14 (Barrow), HA/UoM 15 (Barrow), and HA/UoM 17 (Colligan – Mahon). HA/UoM16 (Suir) is covered by the Suir pilot CFRAM Study and covers an area of approximately 3,452 km<sup>2</sup>. There is a high level of flood risk within the South Eastern CFRAM Study area with significant coastal and fluvial flooding events having occurred in the past.

HA17 (Colligan-Mahon) is covered in this hydrology report. There are no particularly large rivers in the area but rather a number of smaller coastal rivers including the Brickey, Colligan, Dalligan, Mahon and Tay. It is predominantly rural but contains the towns of Dungarvan and Tramore.

Within HA17 there are three Areas for Further Assessment (AFA) as shown in Table 1.1 and Figure 1.1.

**Table 1.1: Fluvial and Coastal Flood Risk at each AFA**

<b>AFA</b>	<b>Fluvial</b>	<b>Coastal</b>
Dungarvan (inc Duckspool and Sallybrook)	✓	✓
Tramore and Environs	✓	✓
Dunmore East	✓	✓

At all three AFAs the flood risk is a result of a combination of fluvial and coastal flooding. It should be noted that the principal source of flood risk at the Dungarvan and Environs AFA was identified as coastal flooding within the Stage II Tender Document for the South-Eastern CFRAM Study but that the Dungarvan and Environs AFA now includes the areas of Killadangan and Sallybrook/Duckspool which were originally listed as areas for risk review due to fluvial flooding.



**Figure 1.1: HA17 AFA Locations**



## **1.1 OBJECTIVE OF THIS HYDROLOGY REPORT**

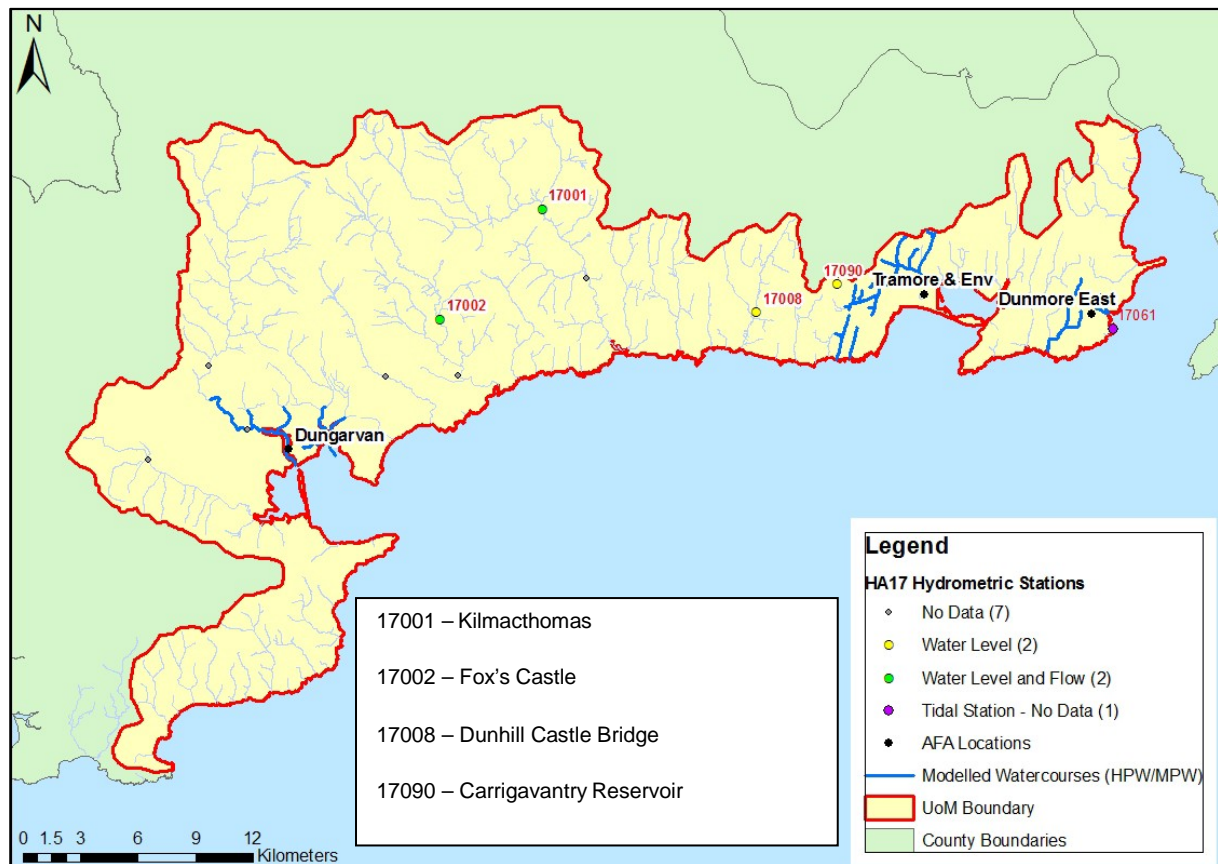
The principal objective of this Hydrology Report is to provide detail on the outputs from the processes of hydrological analysis and design flow estimation. The details of the methodologies used and a summary of the preliminary hydrological analysis are provided in the Inception Report 'IBE0601Rp0006\_HA17\_Inception Report\_F02' (RPS, 2012). This report presents a review and summary of the methodologies used and details any amendments to the methodologies since completion of the Inception Report. The report also provides details of the results of the hydrological analysis and design flow estimation and summarises the outputs from the analysis which will be taken forward as inputs for the hydraulic modelling. Discussion is provided within this report on the outputs in terms of the degree of confidence that can be attached to the outputs and the opportunities for providing greater certainty for future studies, including opportunities for improving the observed data used to inform the study.

This report does not include details of the data collection process, flood history within the AFAs or methodology and results from the historic flood analysis (except where this is used to inform the design flow estimation) as this is contained within the Inception Report for HA17.

## 12 SUMMARY OF THE AVAILABLE DATA

### 1.2.1 Summary of Available Hydrometric Data

Hydrometric data is available at four river hydrometric gauge station locations within HA17 as labelled on Figure 1.2 below.



**Figure 1.2: Hydrometric Data Availability**

However none of these stations are located on the watercourses to be modelled. Two of the four stations have flow data available within HA17. These are at Kilmacthomas and Fox's Castle but both are stated as having extremely poor ratings and as such are unreliable for use as potential donor / pivotal sites in  $Q_{med}$  estimation at ungauged catchments. This is reflected by the fact that they are not on the FSU database of hydrometric stations for use as pivotal sites.

In the South Eastern CFRAM Study project brief (2200/RP/001 March 2011); none of the hydrometric stations within HA17 were specified for CFRAM Study rating review.

There is one tidal station located at Dunmore East (Station No. 17061 –OPW) as shown on Figure 1.2. Data is not available at this station for use in joint probability analysis (refer to Section 5.3).

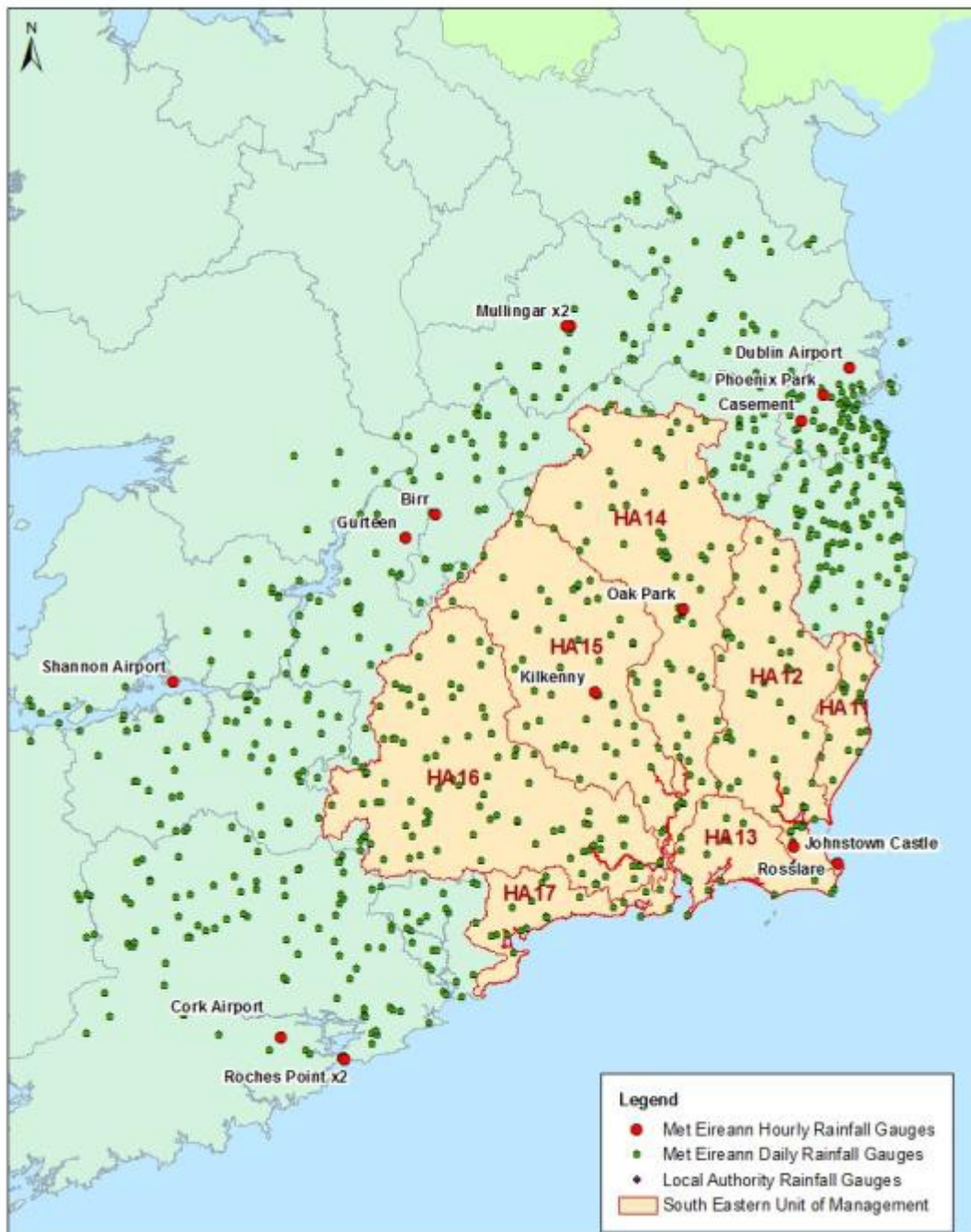
In terms of fluvial hydrology HA17 is essentially ungauged for the purposes of this Study. Further details on the data availability at hydrometric gauge stations within HA17 are contained in Appendix A.

### **1.2.2 Additional Simulated Flow Data**

The Inception Report “IBE0601Rp0006\_HA17\_Inception Report\_F02” (RPS, 2012)”, indicated that additional simulated flow data derived from hydrological rainfall/runoff models was unlikely to be applicable in HA17. Whilst this has been undertaken elsewhere in the South Eastern CFRAM Study area it is not applicable in HA17 since there are no modelled catchments/watercourses for which hydrometric flow data is available such that an accurate rainfall/runoff model can be built and calibrated. Further details on the use of hydrological modelling for the South Eastern CFRAM Study can be found in the Hydrology Reports for HA14 and HA15 (IBE0601Rp00010 and 00011 respectively).

### **1.2.3 Summary of Available Meteorological Data**

Meteorological data is available from a number of Met Éireann daily and hourly rain gauges within the South Eastern RBD as shown in Figure 1.5. There are two Met Éireann hourly rain gauges within HA12 at Johnstown Castle and Rosslare. There is also one in HA14 at Oak Park and one in Kilkenny in HA15. There are none within HA17.



**Figure 1.3: Meteorological Data Availability**

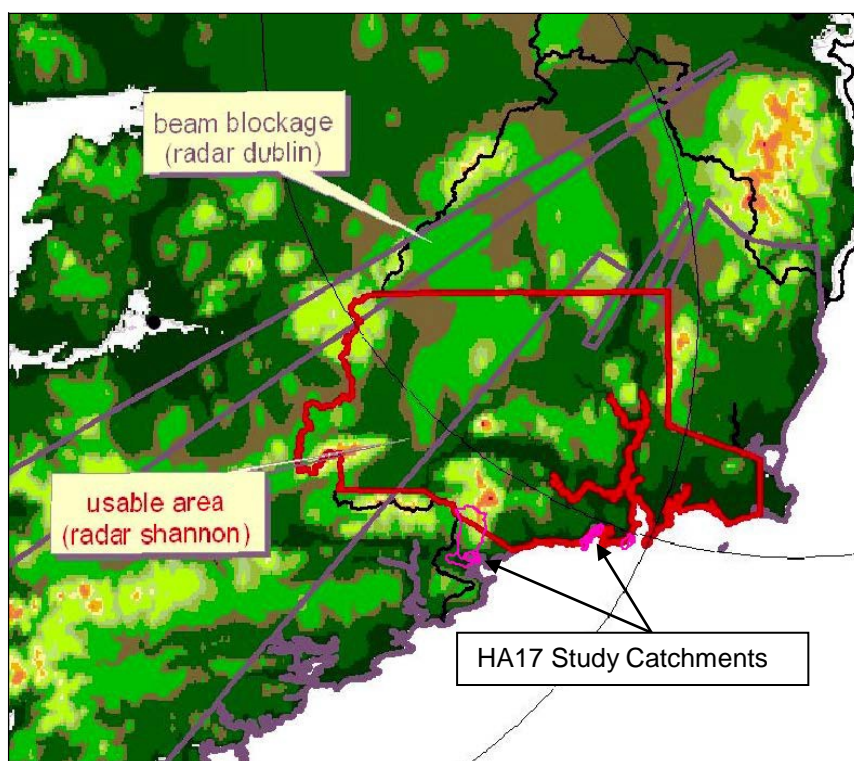
### 1.2.4 Rainfall Radar

A data collection meeting held at the beginning of the Eastern CFRAM Study (between RPS, HydroLogic, OPW and Met Éireann) identified an opportunity for exploring the use and benefits of rainfall radar data in hydrological analysis. A radar trial was undertaken on the Dodder catchment and is reported in 'IBE0600Rp0007 Eastern CFRAM Study, Dublin Radar Data Analysis for the Dodder Catchment, Stage 1' (RPS / Hydrologic, 2012) whereby data from the Dublin radar was adjusted against the available rain gauge data to produce an adjusted hourly gridded time series of rainfall data. When compared to the area-weighted derived rainfall series from the gauge data alone, the use of the radar data was shown to bring significant improvements to the rainfall data for rainfall run-off modelling input in terms of spatial distribution of the rainfall, the peak discharges and the timing of the peak discharges. Simulated hydrograph shapes and the overall water balance error margins were also shown to be significantly improved. A further analysis was also undertaken remote from the Dublin radar in order to quantify the benefits at a location further away from the radar. The Athboy River within HA07 was chosen as a suitable location for the trial and the results of the analysis are presented in the report 'IBE0600Rp0013 Athboy Radar Analysis' (RPS).

Subsequently OPW approved the processing of historical data from the Met Éireann radar stations located at Dublin Airport and Shannon for the entire South Eastern CFRAM Study area using information that was received covering the time period from January 1998 to May 2010. Following initial screening of both the radar information and the available rain gauge information which is required for adjustment of the radar observed rainfall sums; the following dataset was processed for use in the South Eastern CFRAM Study:

- Hourly PCR (Pulse Compression Radar) data on a 1 x 1 km grid (480km x 480km total grid) covering the entire calendar years 1998–2009.

Following processing of this radar dataset rainfall sums are available for every hour, for the majority of 1km<sup>2</sup> grid squares of the South Eastern CFRAM Study area for the calendar years 1998 - 2009. There is a limitation to the extent of radar coverage from Dublin and/or Shannon in the South Eastern CFRAM Study Area. The study catchments in HA17 are covered by neither as shown in Figure 1.4. This is further reason as to why rainfall runoff modelling was not pursued within HA17 (refer to Section 1.2.2).



**Figure 1.4:**            **Extent of Radar Coverage in Relation to HA17 Study Catchments**

## **2 METHODOLOGY REVIEW**

The methodologies for hydrological analysis and design flow estimation were developed based on the current best practice and data availability and are detailed in the HA17 Inception Report. In the intervening period there have been a number of developments both in best practice, and in the hydrological analysis tools which are available such that it is prudent that the overall methodology is reviewed and discussed. As well as a review of the methodology this chapter seeks to identify changes to the catchment that have become apparent and must be considered in the hydrological analysis.

### **21 HYDROLOGICAL ANALYSIS**

The main tasks of hydrological analysis of existing gauge data have been undertaken based on the best practice guidance for Irish catchments contained within the Flood Studies Update. Since HA17 is ungauged, the focus for hydrology analysis is on estimation of the index flow using FSU Work Package 2.3 'Flood Estimation in Ungauged Catchments' as detailed in Section 2.3.1.1 and Chapter 4.

### **22 METEOROLOGICAL ANALYSIS**

Sections 1.2.1 and 1.2.4 discuss how the lack of hydrometric data and rainfall radar data blockage in HA17 contribute to the non-use of rainfall/runoff modelling to derive additional simulated flow data to supplement the hydrology analysis. As such the use of meteorological data has not been pursued further in HA17 as it is not required in the RPS CFRAM methodology if hydrological modelling is not being undertaken.

### **23 DESIGN FLOW ESTIMATION**

The estimation of design flows is based on a methodology combining the available best practice guidance for Irish catchments and hydrological catchment rainfall run-off modelling to augment the available gauged data with simulated flow data. The methodologies for estimation of the various elements which make up the design flow estimates to be used for modelling are detailed below.

#### **2.3.1 Index Flood Flow Estimation**

Estimation of the Index Flood Flow is required for all catchments and sub-catchments to be analysed under the CFRAM Study with each sub-catchment defined by a Hydrological Estimation Point (HEP). The methodologies for estimation of design flow vary depending on whether or not the catchment is gauged and also on how the run-off from the catchments impacts upon an AFA. The hierarchy of methodologies is discussed as follows.

### 2.3.1.1 Ungauged Index Flood Flow ( $Q_{med}$ )

At all catchments the ungauged catchment descriptor based method **FSU WP 2.3 'Flood Estimation in Ungauged Catchments'** has been used, to derive estimates of  $Q_{med}$ , including small ungauged catchments. This is in accordance with recently published guidance "Guidance Note 21 - *CFRAM guidance note on flood estimation for ungauged catchments*". This guidance note drew on the finding that alternative methods for small catchments (Flood Studies Report, NERC, 1975; IH Report 124, Marshall and Baylis, 1994) do not have enough empirical support in Ireland and draw on older and cruder datasets than FSU. Therefore, in the first instance, the FSU 7-variable ungauged catchment descriptor equation (Work Package 2.3) is used to calculate an estimate of the Index Flood Flow at all HEPs and where available, gauge records or catchment run-off models are used to adjust / improve the estimate as the design flow estimation is developed.

The FSU methodology outlined in WP 2.3 recommends that all estimates based on the seven parameter catchment descriptor equation are adjusted based on the most hydrologically similar gauged site. The adjustment factor is applied to the regression equation estimate at the subject catchment and can be described in simple terms as the gauged  $Q_{med}$  divided by the regression equation estimated  $Q_{med}$  at the most hydrologically similar gauged site. Hydrological analysis tools developed by OPW as part of the FSU identify 216 gauge locations which are described as 'Pivotal Sites' following analysis of the data available as part of FSU WP 2.1 'Hydrological Data Preparation'. Since gauged HEPs are not available on the modelled watercourses upon which to base the adjustment RPS have reverted to using the FSU pool of Pivotal Sites based on hydrological similarity.

### 2.3.2 Growth Curve / Factor Development

Growth curves have been developed based on single site and pooled analysis of gauged hydrometric data based on the FSU methodology set out in Work Packages 2.1 and 2.2. Due to CFRAM Study programme constraints it was not possible to include simulated AMAX series years based on rainfall runoff modelling at gauging stations elsewhere in South Eastern CFRAM Study in the analysis and as such all analysis is based on the recorded data only. Full details and discussion of the results can be found in Chapter 5.

### 2.3.3 Design Flow Hydrographs

The design flow hydrograph methodology for HA17 centres around FSU Work Package 3.1 'Hydrograph Width Analysis' and uses the tools developed by OPW for analysing flood hydrographs at gauged sites. Since the completion of the Inception Report the methodology for deriving design flow hydrographs has been developed further following the release of the FSU Hydrograph Shape Generator (version 5). As such the hydrograph shapes are generated based on the following methods:

1. At HEPs representing larger catchments (generally  $10\text{km}^2$  or larger) within HA17 hydrographs will be generated using the recently released Hydrograph Shape generator (version 5) developed by



OPW. This tool increases the list of Pivotal Sites from which median hydrograph shape parameters can be borrowed based on the hydrological similarity of the Pivotal Site when compared to the subject site. The release of version 5 of this tool has increased the pool of Pivotal Sites to over 150. RPS trialling of this version of the FSU Hydrograph Shape Generator in CFRAMS has found that the generated hydrograph shapes provide a reasonably good fit when compared to the observed and simulated (NAM) hydrographs across the Eastern and South Eastern Studyareas.

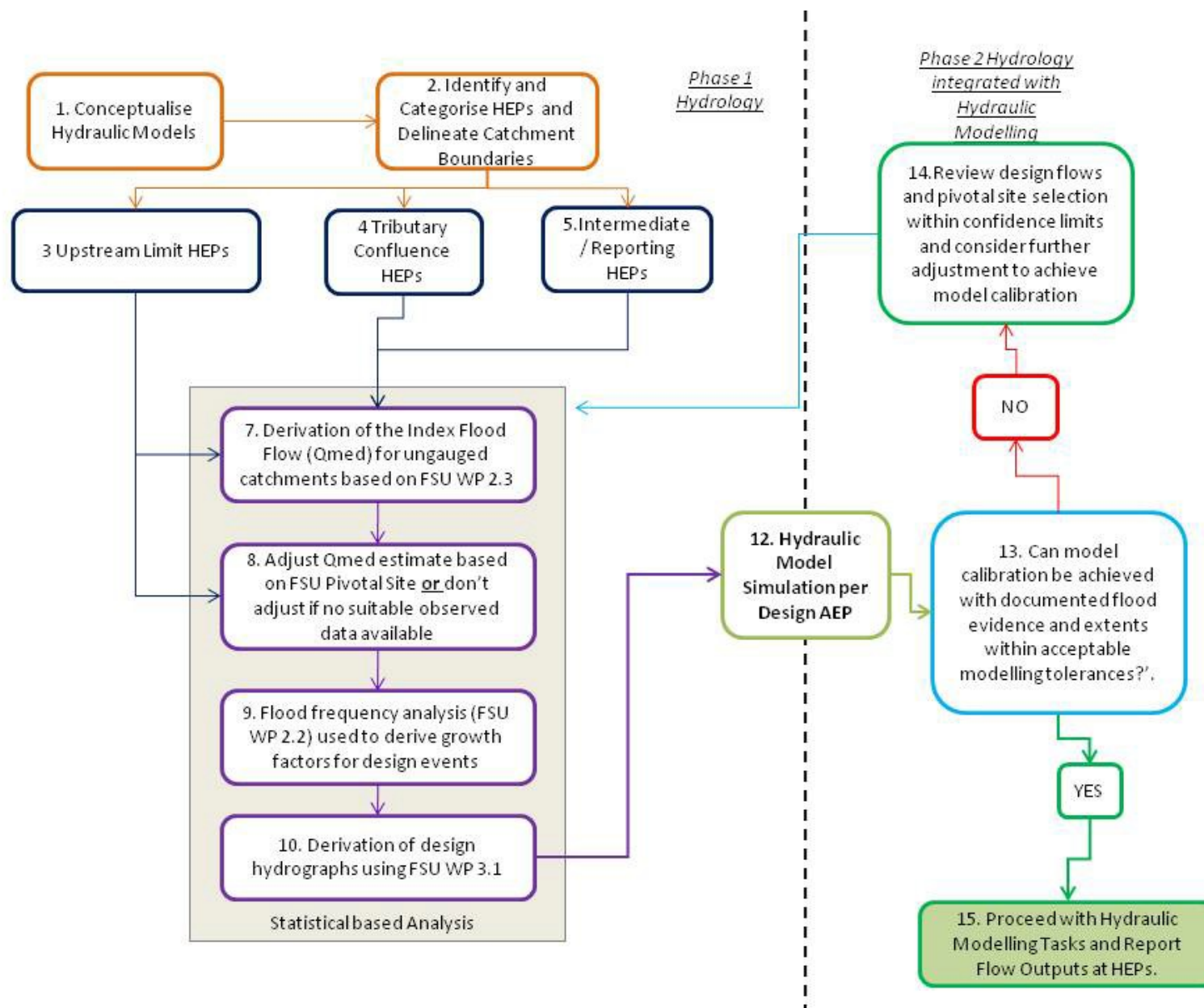
2. At HEPs representing smaller catchments (generally less than 10km<sup>2</sup>) it may not be possible to find a suitable Pivotal Site from which a comparable hydrograph shape can be borrowed, particularly for the very small sub-catchments representing tributary headwaters. In this instance hydrograph shapes have been generated using the Flood Studies Supplementary Report (FSSR) 16 Unit Hydrograph method.

Design hydrographs have been developed at all HEPs. It was originally intended that at the smallest inflow / tributary HEPs continuous point flows could be input. However analysis of this method found that the hydrograph was critical in some of the smallest watercourses which are restricted by culverts / bridges where flood volume as opposed to flood flow becomes the critical characteristic of a flood. An example of this would be partially culverted watercourses in Tramore. Application of continuous point flows on the upstream reaches of the hydraulic models could lead to an unrealistic build up of water behind culvert structures where this is the critical flood mechanism.

Refer to Chapter 5 for details on design hydrograph generation.

## **24 HYDROLOGY PROCESS REVIEW**

Following developments in best practice and guidance documents and the refinement of the RPS methodology through its application on the South Eastern CFRAM Study the hydrology process has been amended slightly from that which was presented in the HA17 Inception Report (summarised previously in Figure 5.2 of report IBE0601Rp0006\_HA17Inception Report\_F02). The revised process flow chart which has been applied in carrying out the hydrological analysis and design flow estimation for HA17 is presented in Figure 2.1.



**Figure 2.1: Hydrology Process Flow Chart HA17**

## 25 CATCHMENT BOUNDARY REVIEW

In line with the CFRAM Study Stage 1 Project Brief (ref. 2149/RP/002/F, May 2010) section 6.3, RPS have delineated the catchment boundaries for HEPs using the FSU derived ungauged and gauged catchment boundaries as a starting point. For details of the full methodology of undertaking this review see HA17 Inception Report section 5.3.2 (IBE0601Rp0006\_HA17Inception Report\_F02). Following the completion of this process a number of the catchment boundaries were amended and in a number of catchments the boundaries were amended significantly. Table 2.1 gives a summary of the changes in the catchment area at CFRAMS HEP points when compared to the equivalent FSU catchment from which they were derived.

**Table 2.1: Summary of Catchment Boundary Review**

<b>Change in Catchment Area</b>	<b>Number of HEPs HA17</b>
New Catchment Delineated	28
No change	1
0 – 10%	11
Greater than 10%	6
<b>Total</b>	<b>46</b>

Not all the catchments related to HEPs that are required to be considered within HA17 were previously delineated. Some of the catchments relate to small streams and land drains which were previously too small to be considered under FSU and as such RPS delineated these catchments using a combination of mapping, aerial photography and the National Digital Height Model (NDHM). The review concluded that 63% of the catchments were already accurately delineated or were newly delineated but 37% of the catchments delineated under FSU were found not to be representative of the NDHM, the mapping or draft survey information. The most common reason for amendment in HA17 was due to inspection of topography from the aforementioned sources. Six of the catchments (6%) were found to have margins of error of over 10%. These catchments ranged from 4.5km<sup>2</sup> to 108km<sup>2</sup> in area.

The overall catchment boundaries for HA17 differ from those provided at project commencement based on FSU catchments as a result of the catchment delineation process. This is illustrated by Figure 2.2.

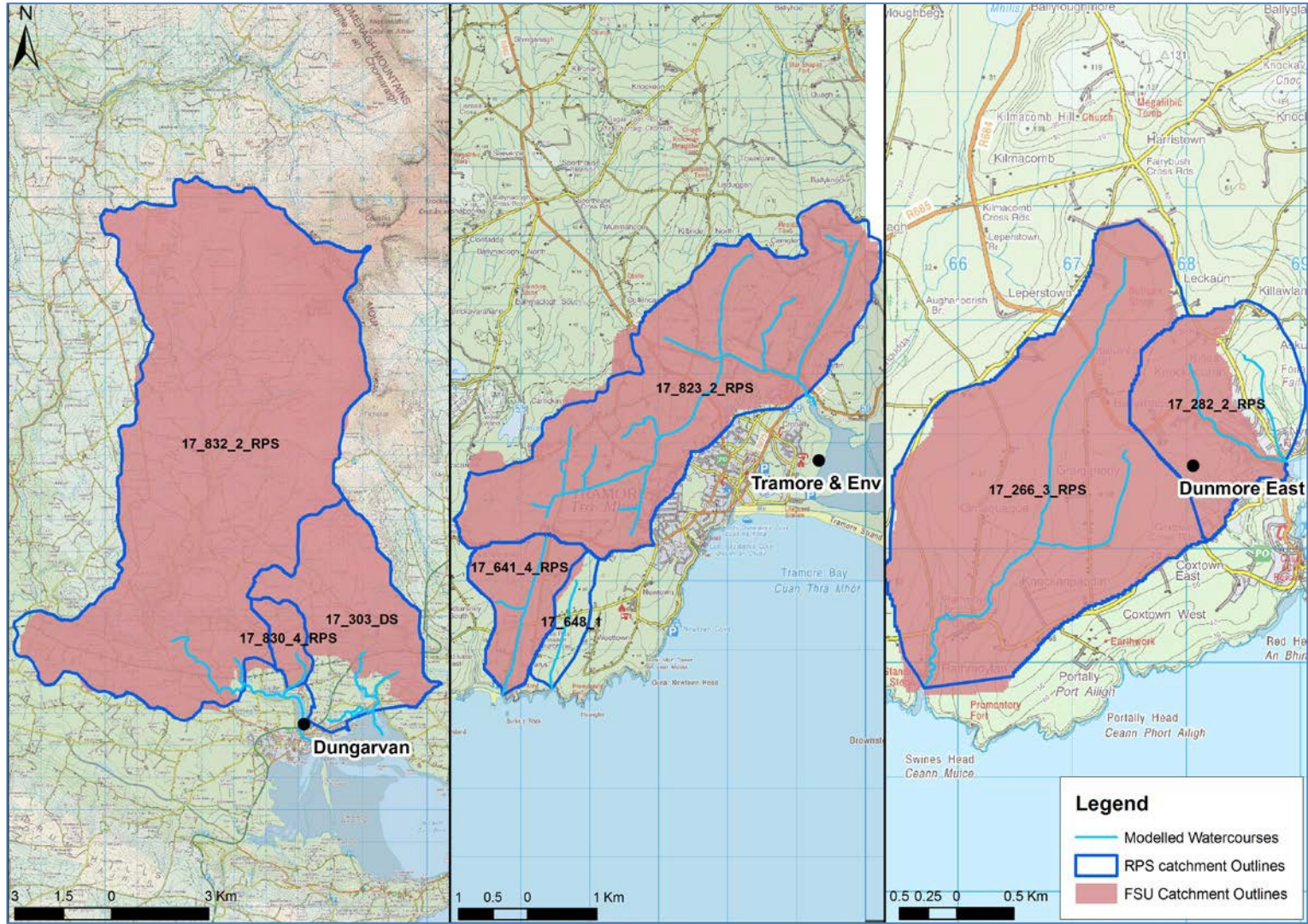


Figure 2.2: Comparison of FSU and RPS Catchment Boundaries

### **3 INDEX FLOOD FLOW ESTIMATION**

The first component in producing design flows within the majority of best practice methods widely used in the UK and Ireland is to derive the Index Flood Flow which within the FSU guidance is defined as the median value of the annual maximum flood flow series or  $Q_{med}$ . The methodologies used in this study are detailed in the HA17 Inception Report and are reviewed in chapter 2 of this report. As discussed the methods used best practice statistical methods. This chapter details the Index Flood Flow estimation at each of the HEPs within HA17 on a model by model basis, including a discussion on the confidence and comparison of the outputs from the considered methodologies.

HA17 has been divided into six hydrodynamic models, primarily based on the requirement within the modelling software to have only one continuous modelled floodplain per model. These were identified in the HA17 Inception Report (IBE0601Rp0006\_HA17Inception Report\_F02). The six models included in HA17 are shown in Figure 3.1.



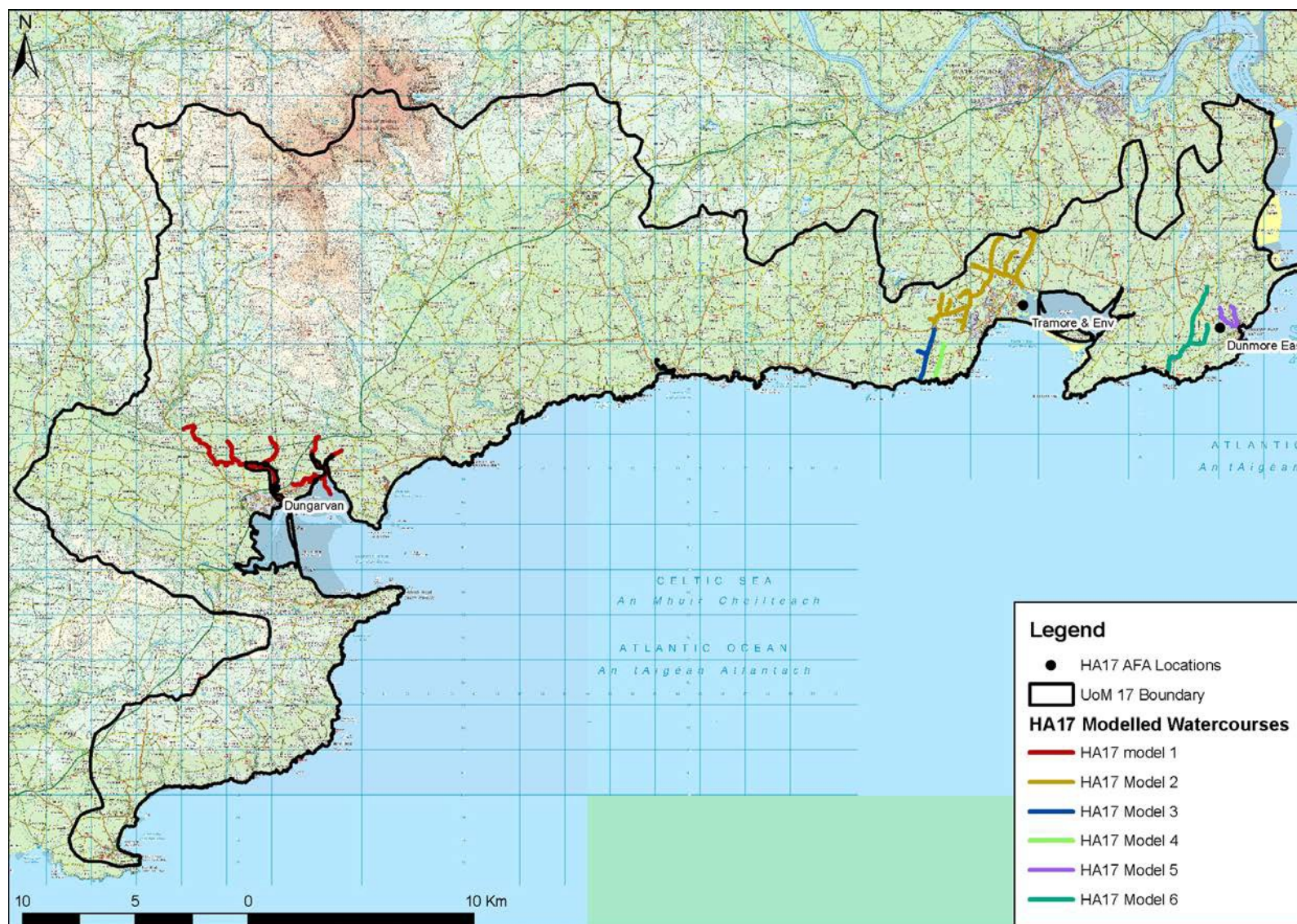


Figure 3.1: HA17 Watercourses to be modelled

### **3.1 MODEL 1 – DUNGARVAN (INCLUDING RINGPHUCA AND DUCKSPOOL)**

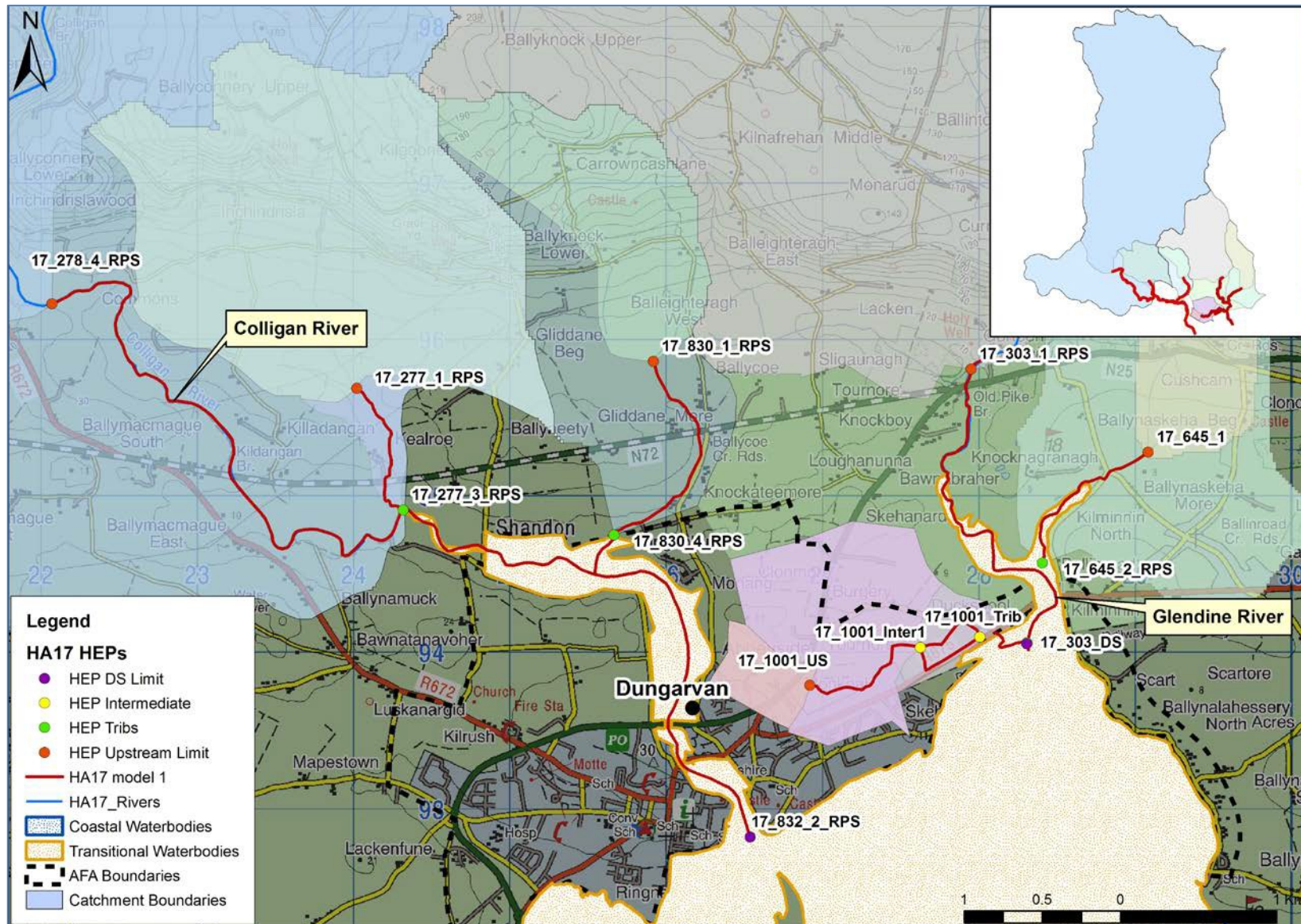
Model 1 constitutes High Priority Watercourses (HPWs) within Dungarvan AFA. It includes the Colligan River from the townland of Commons, beneath the N72 at Kildangan Bridge to its mouth at the Colligan Estuary where it flows through Dungarvan town. It also includes two small tributaries of the Colligan River/Estuary at Kealroe and Ringphuca. Since the Inception Report (IBE0601Rp0006\_HA17 Inception Report\_F02) additional watercourses have been added to Model 1. These constitute three tidally influenced rivers draining to the Colligan Estuary to the east of Dungarvan – the Glendine River and two tributaries at Duckspool.

The contributing catchment to Model 1 at Dungarvan (Colligan River) is 108km<sup>2</sup>. The contributing catchment area of the tributary of the Colligan River at Ringphuca is 3km<sup>2</sup> and the total catchment area of the Glendine River at the downstream limit of the model is 1.7km<sup>2</sup>.

There are no hydrometric stations located within Model 1.

Model 1, its HEPs and catchment boundaries are shown on Figure 3.2.







The estimated  $Q_{med}$  values for the various HEPs within Model 1 are shown in Table 3.1. A review of pivotal site options was undertaken at the most downstream node for each modelled reach with a view to adjusting initial  $Q_{med}$  estimates based on the FSU regression equation using catchment descriptors. The most hydrologically and geographically similar sites yielded a range of adjustment factors such that no clear pattern of under or over-estimation of the initial  $Q_{med}$  value was obvious. In addition, the majority of pivotal site options yielded results outside the 95%ile confidence limits associated with the initial estimate. For this reason, it was decided not to adjust the initial  $Q_{med}$  estimates since there was no clear justification for doing so based on the hydrologically similar pivotal site options.

**Table 3.1:  $Q_{med}$  Values for Model 1**

<b>Node ID_CFRAMS</b>	<b>AREA (km<sup>2</sup>)</b>	<b><math>Q_{med}</math> (m<sup>3</sup>/s)</b>	<b>Preferred Estimation Methodology</b>
17_278_4_RPS	80.846	28.34	FSU
17_277_1_RPS	4.511	1.86	FSU
17_277_3_RPS	4.758	1.86	FSU
17_830_1_RPS	1.517	0.68	FSU
17_830_4_RPS	2.953	0.95	FSU
17_832_2_RPS	108.439	33.12	FSU
17_303_1_RPS	11.587	4.92	FSU
17_645_1	3.219	1.81	FSU
17_645_2_RPS	5.532	2.16	FSU
17_1001_US	0.251	0.08	FSU
17_1001_Inter1	1.466	0.50	FSU
17_1001_Inter2	1.668	0.63	FSU
17_1001_Trib	1.732	0.65	FSU
17_303_DS	21.541	7.54	FSU

Note: Flow highlighted in yellow represent total flows at that point in the model rather than input

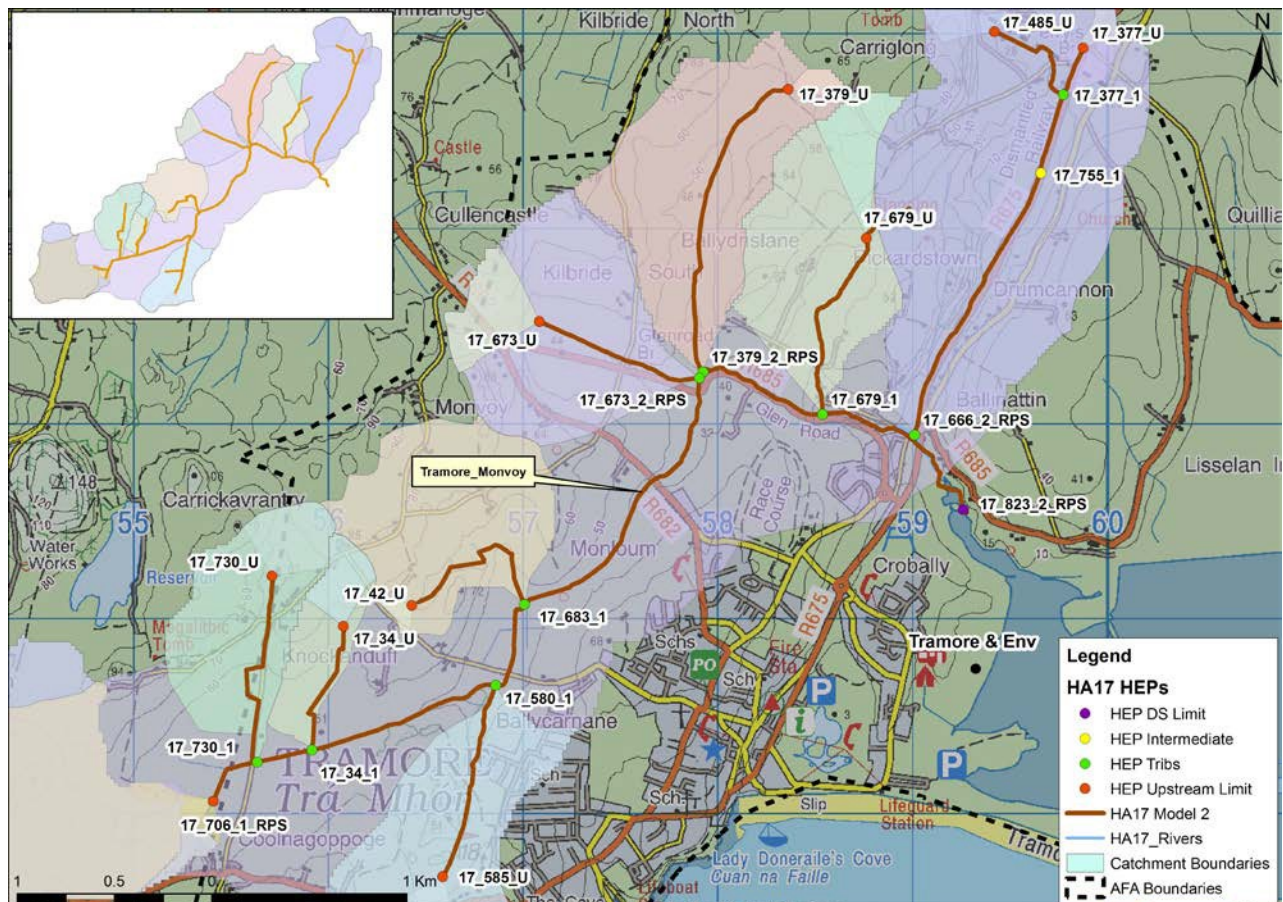
Transitional Water Bodies are also shown on Figure 3.2 illustrating the extent of tidal influence on Model 1. Coastal Hydrology and Joint Probability Analysis for Fluvial-Coastal flood events are discussed further in Sections 5.2 and 5.3 respectively.

### 32 MODEL 2 – TRAMORE

The Tramore model includes the Tramore – Monvoy watercourse which flows around the north of Tramore before following Glen Road and discharging to the east of the town at Tramore Back Strand. Several small tributaries of this watercourse are also part of Model 2. It is a small coastal river system with a total catchment area of 12km<sup>2</sup> at its mouth.

There are no hydrometric stations located within the Model.

The Tramore model, its HEPs and catchment boundaries are shown Figure 3.3 below.



**Figure 3.3: Model 2 HEPs and Catchment Boundaries**

An appropriate pivotal site was selected from a list of geographical and hydrologically similar options. It was decided to select the most hydrologically similar (Station 25034, Rochfort) yielding an adjustment factor of 1.23. A review of seven most hydrologically and geographically similar sites suggest an adjustment factor above 1 presenting a clear indication that upward adjustment was appropriate.

The estimated  $Q_{med}$  values for the various HEPs within Model 2 are shown in Table 3.2.

**Table 3.2:  $Q_{med}$  Values for Model 2**

Node ID_CFRAMS	AREA (km <sup>2</sup> )	$Q_{med}$ (m <sup>3</sup> /s)	Preferred Estimation Methodology
17_706_1_RPS	1.017	0.37	FSU
17_730_U	0.13	0.05	FSU
17_730_1	0.658	0.22	FSU
17_34_U	0.091	0.03	FSU
17_34_1	0.283	0.10	FSU
17_585_U	0.048	0.02	FSU
17_580_1	0.822	0.31	FSU
17_42_U	0.02	0.01	FSU
17_683_1	0.881	0.20	FSU
17_673_U	0.166	0.04	FSU
17_673_2_RPS	1.021	0.25	FSU
17_379_U	0.032	0.01	FSU
17_379_2_RPS	1.088	0.34	FSU
17_679_U	0.148	0.06	FSU
17_679_1	0.863	0.31	FSU
17_485_U	0.229	0.08	FSU
17_377_U	0.034	0.01	FSU
17_377_1	0.084	0.03	FSU
17_755_1	1.018	0.32	FSU
17_799_U	0.054	0.02	FSU
17_799_1	0.399	0.14	FSU
17_666_2_RPS	2.478	0.84	FSU
17_823_2_RPS	12.808	3.91	FSU

Note: Flow highlighted in yellow represent total flows at that point in the model rather than input

Coastal Hydrology and Joint Probability Analysis for Fluvial-Tidal flood events are discussed further in Sections 5.2 and 5.3 respectively.

### 3.3 MODEL 3 AND MODEL 4 – TRAMORE ENVIRONS

The Tramore Environs are represented by Models 3 and 4. These include two adjacent small coastal watercourses which discharge directly to the Eastern Celtic Sea on either side of the Promontory Fort at Garrarus.

The contributing catchment area at the downstream limit Model 3 is 2km<sup>2</sup>. The contributing catchment area at the downstream limit Model 4 is 0.88km<sup>2</sup>. The HEPs and catchment boundaries are shown in Figure 3.4.

There are no hydrometric stations within Model 3 or Model 4.

An appropriate pivotal site was selected from a list of geographical and hydrologically similar options. For both Model 3 and Model 4 it was decided to select the most hydrologically similar (Station 25034, Rochfort) yielding an adjustment factor of 1.23. A review of seven most hydrologically and geographically similar sites suggest an adjustment factor above 1 (but within the 95%ile confidence limit) presenting a clear indication that upward adjustment was appropriate.

The estimated  $Q_{med}$  values for the various HEPs within Model 3 and Model 4 are shown in Table 3.3 and Table 3.4 respectively.

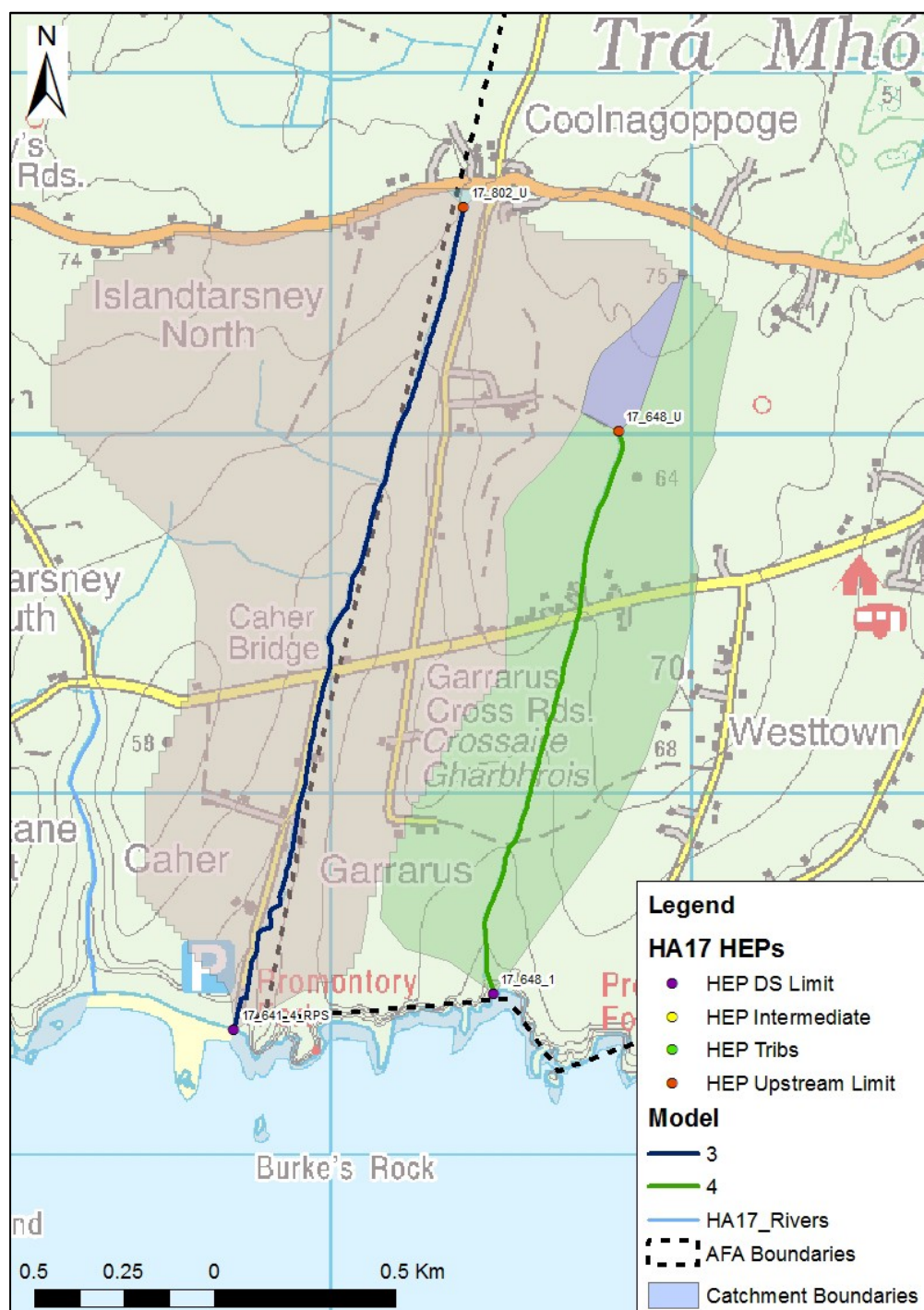
**Table 3.3:  $Q_{med}$  Values for Model 3**

Node ID_CFRAMS	AREA (km <sup>2</sup> )	$Q_{med}$ (m <sup>3</sup> /s)	Preferred Estimation Methodology
17_802_U	0.003	0.002	FSU
17_641_4_RPS	2.154	0.87	FSU

**Table 3.4:  $Q_{med}$  Values for Model 4**

Node ID_CFRAMS	AREA (km <sup>2</sup> )	$Q_{med}$ (m <sup>3</sup> /s)	Preferred Estimation Methodology
17_648_U	0.05	0.022	FSU
17_648_1	0.88	0.32	FSU

Note: Flow highlighted in yellow represent total flows at that point in the model rather than input flows – in this case the total flow shall be applied to the model given the small size.



**Figure 3.4: Model 3 and Model 4 HEPs and Catchment Boundaries**



### 34 MODEL 5 AND MODEL 6 – DUNMORE EAST

Model 5 represents two watercourses that flow through Dunmore East before discharging to the sea. They are small coastal catchments which meet to the north of Dunmore East Village. The total catchment area at the downstream limit of Model 5 is just over 2km<sup>2</sup>. Model 6 represents the Rathmoylan River and its tributary, located to the west of Dunmore East which discharges directly to the Eastern Celtic Sea at Rathmoylan. The total catchment area at the downstream limit of Model 6 is 6.5km<sup>2</sup>.

There are no hydrometric stations within Model 5 or Model 6.

The HEPs and catchment boundaries are shown in Figure 4.5.

An appropriate pivotal site was selected from a list of geographical and hydrologically similar options. For Model 5 it was decided to select the most hydrologically similar (Station 25034, Rochfort) yielding an adjustment factor of 1.23. A review of the seven most hydrologically and geographically similar sites suggest an adjustment factor above 1 presenting an indication that upward adjustment was appropriate. For Model 6 an adjustment factor of 1.073 has been applied as derived from the two most hydrologically similar FSU sites which were not urbanised. Again, a review of the seven most hydrologically and geographically similar suggests an adjustment factor above 1 presenting an indication that upward adjustment was appropriate.

The estimated  $Q_{med}$  values for the various HEPs within Model 5 and Model 6 are shown in Table 3.5 and Table 3.6 respectively.

**Table 3.5:  $Q_{med}$  Values for Model 5**

Node ID_CFRAMS	AREA (km <sup>2</sup> )	$Q_{med}$ (m <sup>3</sup> /s)	Preferred Estimation Methodology
17_282_U	0.061	0.03	FSU
17_288_U	0.096	0.05	FSU
17_288_1	0.685	0.31	FSU
17_282_2_RPS	2.074	0.88	FSU

Note: Flow highlighted in yellow represent total flows at that point in the model rather than input flows

**Table 3.6:  $Q_{med}$  Values for Model 6**

Node ID_CFRAMS	AREA (km <sup>2</sup> )	$Q_{med}$ (m <sup>3</sup> /s)	Preferred Estimation Methodology
17_186_U	0.067	0.02	FSU
17_134_U	0.011	0.003	FSU
17_134_2_RPS	1.226	0.31	FSU
17_266_3_RPS	6.451	1.57	FSU

Note: Flow highlighted in yellow represent total flows at that point in the model rather than input flows

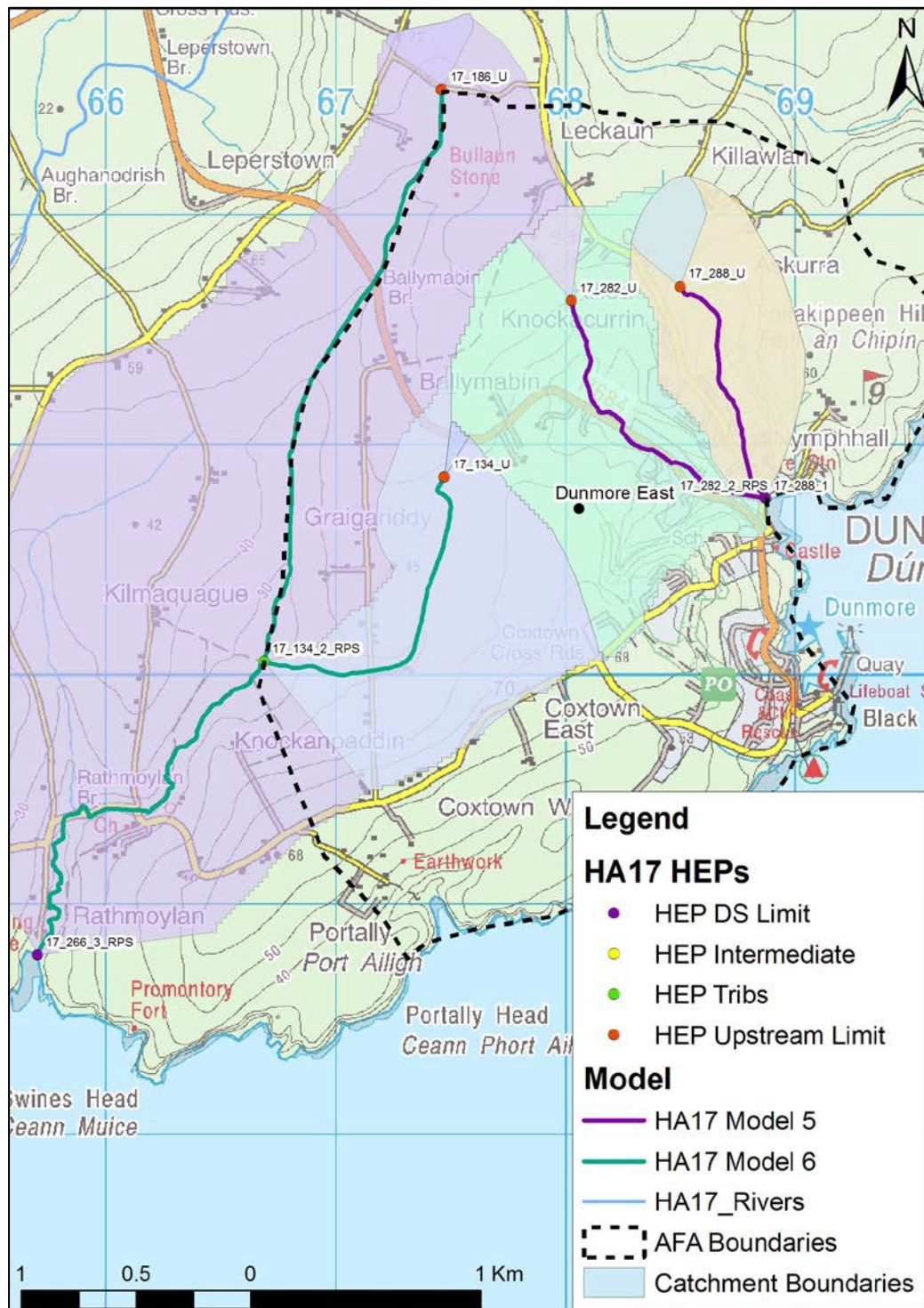


Figure 3.5: Model 5 and Model 6 HEPs and Catchment Boundaries

## **3.5 INDEX FLOOD FLOW CONFIDENCE LIMITS**

### **3.5.1 Ungauged $Q_{med}$**

The estimation of  $Q_{med}$  for the ungauged catchments within this study focuses on the FSU (WP 2.3) statistical based method where a regression equation is used based on catchment descriptors.

The FSU method for Flood Estimation in Ungauged Catchments (WP 2.3) is based on a regression equation derived from data from 190 hydrometric gauge stations across Ireland, only eight of which are for catchments less than 25km<sup>2</sup>. The factorial standard error (FSE) associated with  $Q_{med}$  estimation using FSU (WP 2.3) is 1.37. The IH124 method has traditionally been preferred for catchments less than 25km<sup>2</sup> in area as the data upon which the regression equation was derived is much more weighted towards smaller catchments. This has a higher factorial standard error of 1.64. However recent guidance has shifted towards the use of FSU WP 2.3 for all Irish ungauged catchments as discussed in Section 2.3.1.1 (based on recent CFRAM Study Guidance), and as such it has been applied to all ungauged catchments in this Study. In cases where adjustment of initial  $Q_{med}$  estimates using pivotal sites result in final  $Q_{med}$  values outside confidence limits derived using the factorial standard error of 1.37, they have not been used.



## **4 FLOOD FREQUENCY ANALYSIS AND GROWTH CURVE DEVELOPMENT**

### **4.1 OBJECTIVE AND SCOPE**

This chapter deals with the estimation of flood growth curves for a number of river catchments located within HA17. The estimated growth curves will be used in determining the peak design flood flows for all Hydrological Estimation Points (HEP) located on the modelled tributary and main river channels within HA17.

The scope of this chapter includes:

- (i) Selection of a statistical distribution suitable for regional flood frequency analysis,
- (ii) Selection of pooling region and groups, and
- (iii) Growth curve estimation,

### **4.2 METHODOLOGY**

#### **4.2.1 Selection of Statistical Distribution**

The suitable distributions for the Annual Maximum (AMAX) series for all hydrometric gauging sites located within HA17 were determined based on the statistical distribution fitting technique described in the Flood Studies Update (FSU) Programme Work Package 2.2 “Frequency Analysis” (OPW, 2009), UK Flood Estimation Handbook (FEH) (Institute of Hydrology, 1999) and 1975 Flood Studies Report (NERC, 1975).

#### **4.2.2 Forming a Pooling Region and Groups**

The pooling group associated with each of the growth curves was formed based on the Region-of-Influence (ROI) approach (Burn, 1990) recommended in FSU (2009). The region from which the AMAX series were pooled to form a pooling group for each of the growth curves was selected based on the similarity in catchment characteristics (both climatic and physiographic) in the neighbouring geographical region.

#### **4.2.3 Growth Curve Development**

Growth curves for each of the HEP locations were developed / estimated in accordance with the methodologies set out in the FSU, FSR and FEH studies. The Hosking and Wallis (1997) proposed L-Moment theories were used in estimating the parameters of the statistical distributions. The growth curve estimation process was automated through development of a FORTRAN 90 language based computational program.

#### 4.2.4 Limitations in the FEH and FSU Studies

There is no explicit guidance provided in FEH or FSU for dealing with the issues surrounding production of a large number of growth factors within a river system and the associated problems with consistency and transition from growth curve to growth curve. For the subject river catchments located within HA17, a catchment characteristic based generalised growth curve estimation method, as discussed later in Sections 4.7.4 and 4.8, was used to deal with this real world problem.

### 4.3 DATA AND STATISTICAL PROPERTIES

#### 4.3.1 Flood Data

The AMAX series for all hydrometric gauging sites located within HA17 were obtained from the OPW and the EPA. In addition to these, flow records from neighbouring catchments were also collected to form a pooling region for growth curve analysis. The AMAX series and continuous flood records for 92 gauging sites were obtained for up to year 2011. Table 4.1 overleaf presents the locations details, record lengths and some of the catchment characteristics of these hydrometric stations, while Figure 4.1 illustrates their spatial distributions in the region. The majority of the 92 stations have A1 & A2 rating quality classification defined as:

**A1 sites** – Confirmed ratings good for flood flows well above  $Q_{med}$  with the highest gauged flow greater than  $1.3 \times Q_{med}$  and/or with a good confidence of extrapolation up to 2 times  $Q_{med}$ , bank full or, using suitable survey data, including flows across the floodplain.

**A2 sites** – ratings confirmed to measure  $Q_{med}$  and up to around 1.3 times the flow above  $Q_{med}$ . Would have at least one gauging to confirm and have a good confidence in the extrapolation.

Those that are B rated are defined as:

**B sites** – Flows can be determined up to  $Q_{med}$  with confidence. Some high flow gaugings must be around the  $Q_{med}$  value. These are sites where the flows and the rating was well defined up to  $Q_{med}$  i.e. the highest gauged flow was at least equal to or very close to  $Q_{med}$ , say at least  $0.95 Q_{med}$  and no significant change in channel geometry was known to occur at or about the corresponding stage.

The record lengths in these gauging stations vary from 9 to 70 years with a total of 3,336 station-years of AMAX series. In HA17, only one river catchment has 10 station-years of AMAX series (Tay River at Fox Castle). As stated in Section 1.2.1, this station has a poor rating and as such is unreliable for use as a potential donor / pivotal site in  $Q_{med}$  estimation at ungauged catchments. However it has been kept within the pooling group since its effect is minimal, but it has not been used for any specific estimated growth curve adjustment.

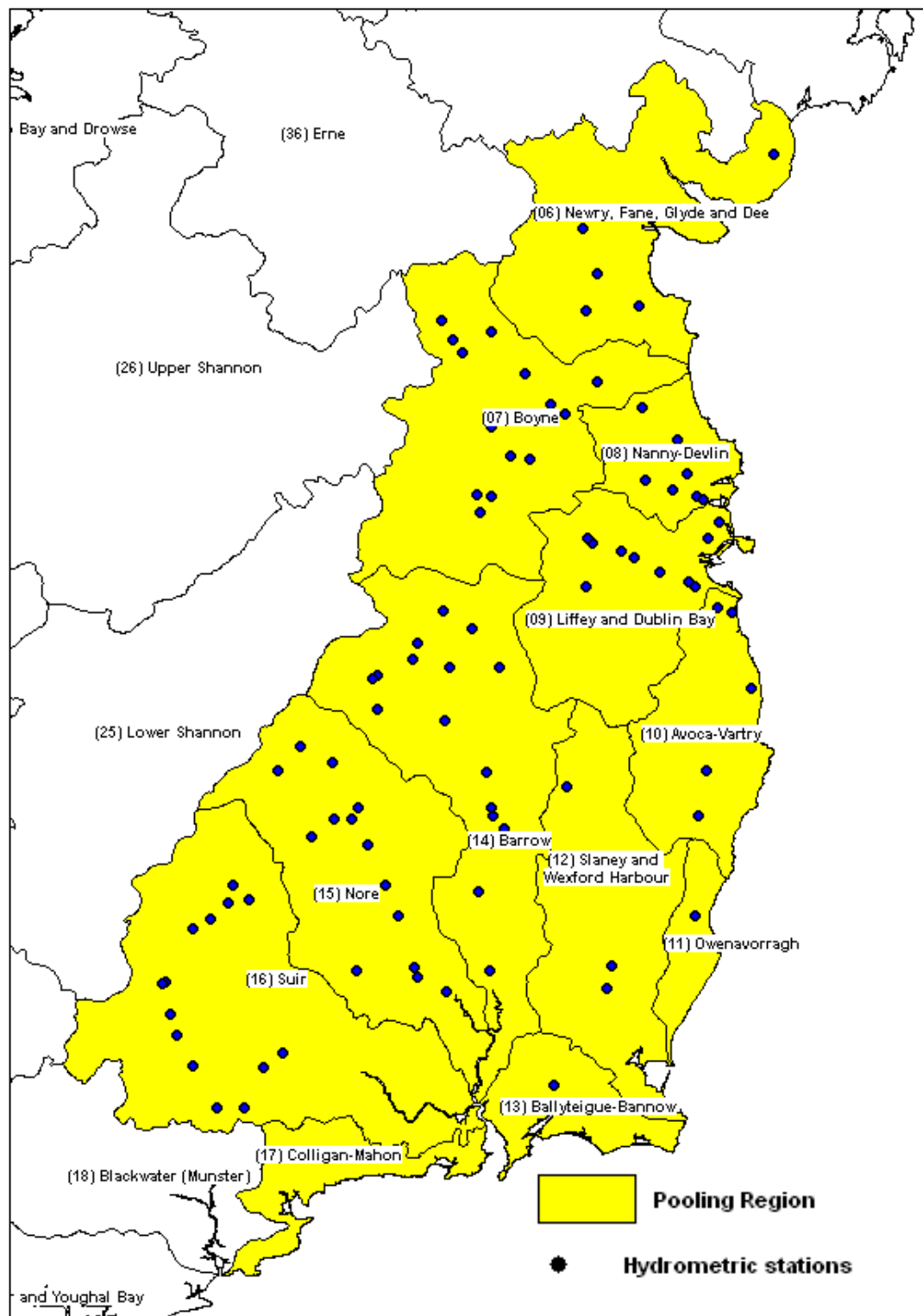
There are climatic differences between the eastern and other parts of the country and restricting the choice of pooling stations to the eastern and south-eastern regions along with HA06 should ensure an additional degree of homogeneity. In particular, it was felt that the catchments of the Shannon hydrometric areas, many of which are large and flat, would not necessarily be homogeneous with the Eastern and South-Eastern HAs and therefore would not make any additional useful contribution to the development of their growth curves. In light of the large number of AMAX values (3,336 station-years) available in the eastern and south-eastern HAs, it is not considered necessary to extend the pooling region to the entire country.

**Table 4.1: Hydrometric Station Summary**

Stations	Waterbody	Location	Record Length (Years)	Area (km <sup>2</sup> )	SAAR (mm)	BFI	FARL	FSU Gauge Rating Classification
6011	Fane	Moyles Mill	51	229.19	1028.98	0.708	0.874	A1
6012	Annalong	Subsidiary Intake	53	162.80	1046.24	0.680	0.831	Not Classified
6013	Dee	Charleville	35	309.15	873.08	0.617	0.971	A1
6014	Glyde	Tallanstown	35	270.38	927.45	0.634	0.927	A1
6025	Dee	Burley	36	175.98	908.31	0.615	0.956	A1
7001	Tremblestown	Tremblestown	42	151.31	913.24	0.700	0.996	A2
7002	Deel [Raharney]	Killyon	51	284.97	920.53	0.780	0.929	A2
7003	Blackwater (Enfield)	Castlerickard	51	181.51	809.22	0.649	1.000	A1 & B
7004	Blackwater (Kells)	Stramatt	53	245.74	1007.88	0.619	0.772	A2
7005	Boyne	Trim	52	1332.17	879.71	0.721	0.983	A1
7006	Moynalty	Fyanstown	49	177.45	936.67	0.552	0.990	A2
7007	Boyne	Boyne Aqueduct	50	441.18	870.98	0.663	1.000	A1 & B
7009	Boyne	Navan Weir	34	1658.19	868.55	0.713	0.911	A1
7010	Blackwater (Kells)	Liscartan	51	699.75	948.29	0.658	0.798	A1 & A2
7011	Blackwater (Kells)	O'daly's Br.	49	281.74	1003.32	0.678	0.965	A2 & B
7012	Boyne	Slane Castle	70	2460.27	890.06	0.678	0.893	A1
7017	Moynalty	Rosehill	11	70.64	991.74	0.516	0.993	Not Classified
7023	Athboy	Athboy	9	100.10	950.81	0.717	0.995	Not Classified
7033	Blackwater (Kells)	Virginia Hatchery	30	124.94	1032.22	0.439	0.893	A2
8002	Delvin	Naul	24	33.43	791.12	0.597	1.000	A1
8003	Broadmeadow	Fieldstown	18	83.59	826.00	0.466	0.880	B
8005	Sluice	Kinsaley Hall	23	9.17	710.76	0.523	1.000	A2
8007	Broadmeadow	Ashbourne	21	37.94	845.02	0.399	1.000	B
8008	Broadmeadow	Broadmeadow	28	107.92	810.61	0.487	0.999	A2

Stations	Waterbody	Location	Record Length (Years)	Area (km <sup>2</sup> )	SAAR (mm)	BFI	FARL	FSU Gauge Rating Classification
8009	Ward	Balheary	15	61.64	767.09	0.545	0.999	A1
8010	Garristown St.	Garristown S.W.	13	1.13	818.92	0.682	1.000	Not Classified
8011	Nanny	Duleek D/S	28	181.77	819.49	0.520	0.999	B
8012	Stream	Ballyboghill	17	25.95	798.70	0.524	0.999	B
9001	Ryewater	Leixlip	54	209.63	783.26	0.507	1.000	A1
9002	Griffeen	Lucan	25	34.95	754.75	0.674	0.958	A1
9010	Dodder	Waldron's Bridge	57	94.26	955.04	0.561	0.993	A1
9011	Slang	Frankfort	19	5.46	772.95	0.563	0.986	B
9024	Morell	Morell Bridge	9	98.75	851.99	0.705	0.987	Not Classified
9035	Camac	Killeen Road	15	37.14	794.21	0.673	0.932	B
9048	Ryewater	Anne's Bridge	10	59.35	805.54	0.474	1.000	Not Classified
9049	Lyreen	Maynooth	10	87.52	768.17	0.473	1.000	Not Classified
10002	Avonmore	Rathdrum	52	230.89	1530.19	0.538	0.986	B
10004	Glenmacnass	Laragh	14	30.57	1700.39	0.436	0.997	Not Classified
10021	Shanganagh	Common's Road	30	32.51	799.07	0.654	0.997	A1
10022	Cabinteely	Carrickmines	17	12.94	821.92	0.600	1.000	A1
10028	Aughrim	Knocknamohill	22	202.92	1396.92	0.788	0.999	B
10038	Stream	Druids Glen	10	16.14	914.40	0.618	1.000	Not Classified
11001	Owenavorrigh	Boleany	38	155.11	931.07	0.489	0.999	A1
12001	Slaney	Scarawalsh	55	1030.75	1167.31	0.716	0.999	A2
12002	Slaney	Enniscorthy	31	1319.92	1129.33	0.714	1.000	Not Classified
12013	Slaney	Rathvilly	35	204.39	1383.48	0.743	0.999	B
13002	Corock	Foulk's Mill	25	62.96	1043.79	0.733	1.000	Not Classified
14003	Barrow	Borness	27	206.73	1160.51	0.532	1.000	Not Classified
14004	Figile	Clonbulloge	53	268.85	838.67	0.537	1.000	Not Classified
14005	Barrow	Portarlinton	53	405.48	1014.90	0.501	1.000	A2
14006	Barrow	Pass Br	56	1063.59	899.07	0.571	1.000	A1
14007	Stradbally	Derrybrock	30	118.59	814.07	0.642	1.000	A1
14009	Cushina	Cushina	30	68.35	831.24	0.667	1.000	A2
14011	Slate	Rathangan	31	162.30	806.97	0.600	0.999	A1
14013	Burren	Ballinacarrig	55	154.40	887.98	0.701	0.999	A2
14018	Barrow	Royal Oak	67	2419.40	857.46	0.665	1.000	A1
14019	Barrow	Levitstown	57	1697.28	861.46	0.624	0.999	A1
14022	Barrow	Barrow Bridge New	12	2069.53	855.63	0.652	0.999	Not Classified
14029	Barrow	Graiguenamanagh U/S	52	2778.15	876.50	0.688	0.999	A2
14031	Tully	Japanese Gdns	10	13.00	826.06	0.650	1.000	Not Classified
14033	Owenass	Mountmellick	10	78.89	1145.22	0.454	0.999	B

Stations	Waterbody	Location	Record Length (Years)	Area (km <sup>2</sup> )	SAAR (mm)	BFI	FARL	FSU Gauge Rating Classification
14034	Barrow	Bestfield Lock	17	2057.36	856.05	0.652	0.999	A2
14101	Boghlone	Kyleclonhobert	9	9.60	929.15	0.554	1.000	Not Classified
15001	Kings	Annamult	48	444.35	935.24	0.514	0.997	A2
15002	Nore	John's Br.	53	1644.07	945.44	0.625	0.730	A2
15003	Dinin	Dinin Br.	56	299.17	933.86	0.381	0.998	A2
15004	Nore	Mcmahons Br.	56	491.38	1067.46	0.594	0.999	A2
15005	Erkina	Durrow Ft. Br.	55	379.37	884.96	0.712	0.999	B
15006	Nore	Brownsbarn	54	2418.27	941.92	0.633	0.997	Not Classified
15007	Nore	Kilbricken	35	339.76	1123.04	0.594	1.000	A2
15008	Nore	Borris In Ossory	35	116.22	943.75	0.533	0.993	Not Classified
15009	Kings	Callan	54	203.14	940.19	0.540	1.000	Not Classified
15010	Goul	Ballyboodin	31	159.06	886.97	0.657	0.997	Not Classified
15011	Nore	Mount Juliet	57	2225.79	938.02	0.618	0.999	Not Classified
15012	Nore	Ballyragget	16	1056.80	974.00	0.682	0.999	B
15021	Delour	Annagh	11	67.05	1358.56	0.651	1.000	Not Classified
15041	Goul	Ballinfrase	9	135.39	889.60	0.634	0.996	Not Classified
16001	Drish	Athlummon	38	135.06	916.42	0.606	1.000	A2
16002	Suir	Beakstown	56	485.70	932.15	0.634	0.999	A2
16003	Clodiagh	Rathkennan	56	243.20	1192.01	0.550	1.000	A2
16004	Suir	Thurles	55	228.74	941.36	0.579	1.000	A2
16005	Multeen	Aughnagross	35	84.00	1153.57	0.560	0.994	A2
16006	Multeen	Ballinaclogh	38	75.80	1115.82	0.587	0.999	B
16007	Aherlow	Killardry	56	273.26	1330.55	0.578	0.999	B
16008	Suir	New Bridge	56	1090.25	1029.63	0.635	0.998	A2
16009	Suir	Caher Park	57	1582.69	1078.57	0.631	0.998	A2
16010	Anner	Anner	38	437.10	985.24	0.624	0.999	Not Classified
16011	Suir	Clonmel	71	2143.67	1124.95	0.670	0.993	A1
16012	Tar	Tar Br.	46	229.63	1320.79	0.628	0.999	B
16013	Nire	Fourmilewater	45	93.58	1471.29	0.539	0.993	B
16051	Rossestown	Clobanna	13	34.19	895.27	0.676	1.000	B
17002	Tay River	Fox Castle	10	33.50	1554.00	0.604	1.000	Not Classified



**Figure 4.1: Locations of 92 Gauging Stations**

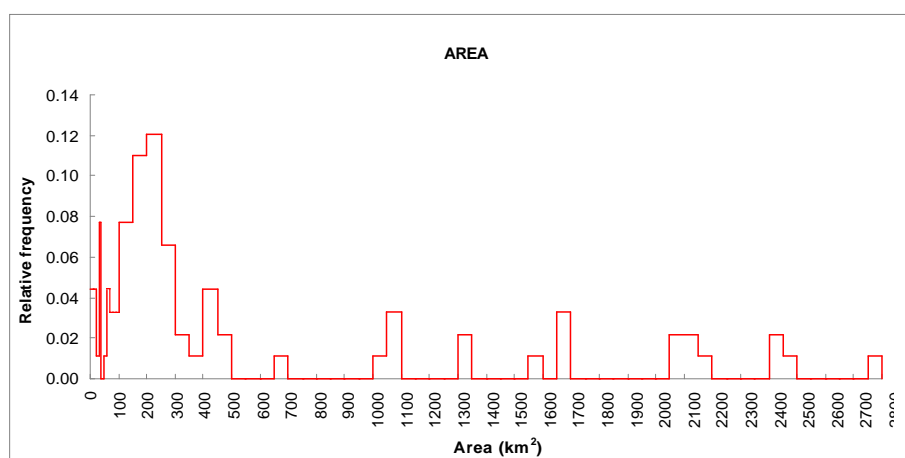
### 4.3.2 Pooling Region Catchment Physiographic and Climatic Characteristic Data

In addition to the AMAX series, some catchment physiographic and climatic characteristics including the catchment sizes (AREA), Standard Average Annual Rainfall (SAAR), catchment Base Flow Index (BFI) and the Flood Attenuation by Reservoirs and Lakes (FARL) Index for all 92 stations were also obtained from OPW. Table 4.2 presents a summary of these catchment characteristics. Catchment sizes range from 1.13 to 2778.15 km<sup>2</sup> with a median value of 182 km<sup>2</sup>, SAAR values range from 711 to 1700 mm with a median value of 927 mm. The BFI values vary from 0.381 to 0.788, while the FARL values range from 0.730 to 1.0.

**Table 4.2: Summary of Catchment physiographic and climatic characteristics of Pooling Region**

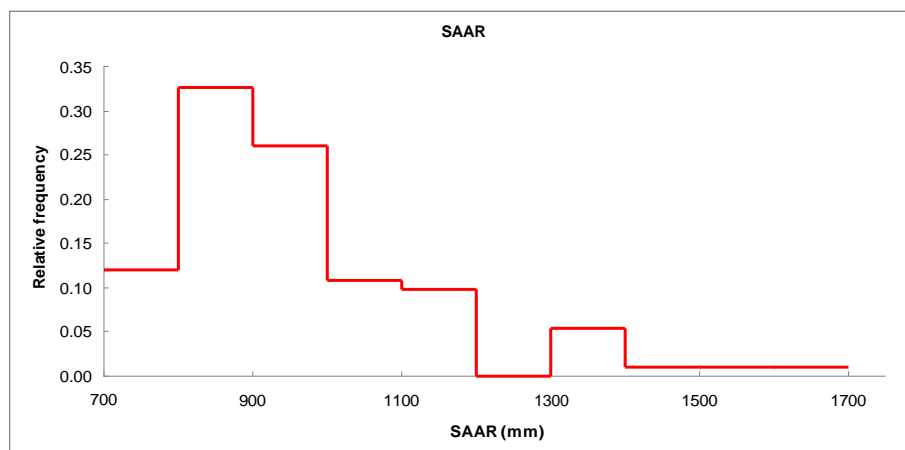
Characteristics	Minimum	Maximum	Mean	Median
AREA (km <sup>2</sup> )	1.13	2778.15	489.17	181.77
SAAR (mm)	710.76	1700.39	967.15	927.45
BFI	0.381	0.788	0.608	0.624
FARL	0.730	1.000	0.979	0.999

Furthermore the relative frequencies of the AREA, SAAR and BFI values within the 92 stations are also presented in Figure 4.2, Figure 4.3 and Figure 4.4 respectively. It can be seen from Figure 4.2 that the majority of the catchment areas in the selected sites fall in the range of 100 to 500 km<sup>2</sup>. Figure 4.3 shows that the SAAR values in majority of the stations range from 800 to 1000 mm and very few stations have SAAR values more than 1400 mm. Similarly, Figure 4.4 shows the relative frequency of the BFI values within the 92 catchments. It can be seen from this figure that the BFI values in the majority of the 92 catchment areas range from 0.5 to 0.75.

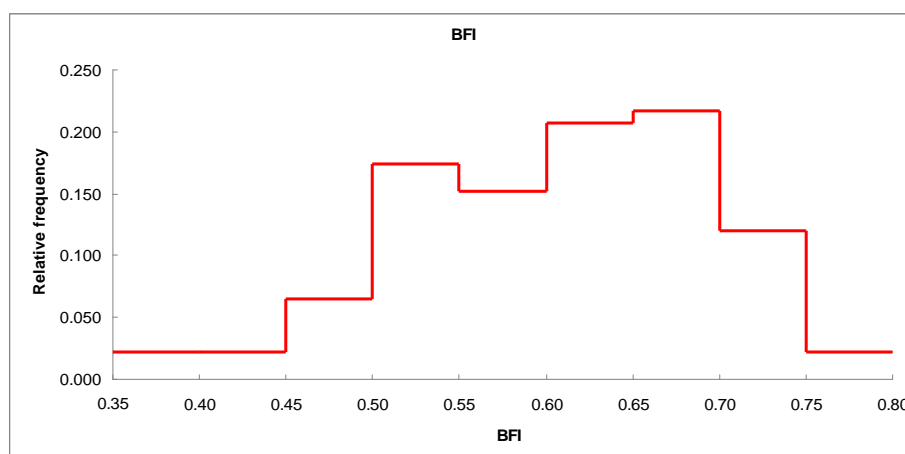


**Figure 4.2: Relative frequencies of catchments sizes (AREA) within the selected 92 stations**





**Figure 4.3: Relative frequencies of the SAAR values within the selected 92 stations**



**Figure 4.4: Relative frequencies of the BFI values within the selected 92 stations**

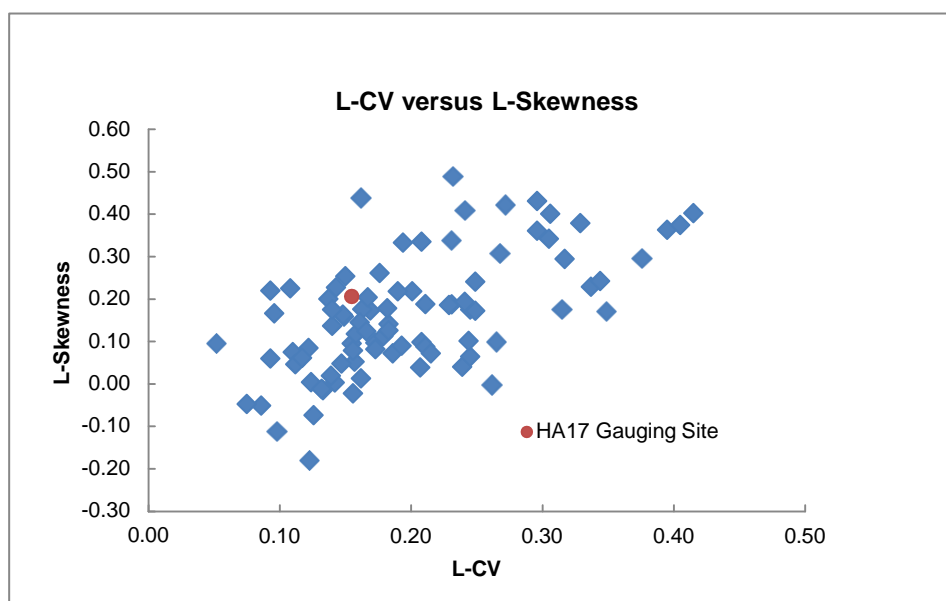
There are five gauges in the pooling group located within areas that have karst aquifers. The BFI values at these gauges have been accounted for in the pooling group - aquifer type is a contributing factor in this index and is therefore inherently taken into account. The associated BFI values are in keeping with the rest of the pooling group as shown above indicating that the karst element is not significant. Furthermore, the karst areas do not cover significant parts of the catchments associated with these gauging sites. Any impacts on the estimated growth curves due to the inclusion of these sites in the pooling group would be minimal and so they have been retained in the pooling group.

#### 4.3.3 Statistical Properties of the AMAX series

Table 4.3 provides a summary of the statistical properties of the AMAX series for all 92 gauging sites. The median annual maximum flows ( $Q_{med}$ ) range from 0.47 to 299.32 m<sup>3</sup>/s with an average value of 53.83 m<sup>3</sup>/s. The L-CV values range from 0.052 to 0.415 with an average value of 0.198, while the L-Skewness values range from -0.181 to 0.488 with an average value of 0.166 which is approximately equal to the theoretical L-Skewness of EV1 distribution. Figure 4.5 shows the L-CV versus L-Skewness diagram for the 92 AMAX series with the values associated with the HA17 river catchment shown in red.

**Table 4.3: Statistical properties of 92 AMAX Series**

Parameters	Minimum	Maximum	Mean	Median
Record Lengths (years)	9	71	37	35
Mean Flow (m <sup>3</sup> /s)	0.49	303.45	56.56	27.16
Median Flow (m <sup>3</sup> /s)	0.47	299.32	53.83	25.42
L-CV	0.052	0.415	0.198	0.182
L-skewness	-0.181	0.488	0.166	0.163
L-kurtosis	-0.127	0.426	0.155	0.139

**Figure 4.5: L-Moment Ratio Diagram (L-CV versus L-Skewness) for 92 AMAX series**

## 4.4 STATISTICAL DISTRIBUTION

The individual gauging site's AMAX series were fitted to four flood like distributions, namely EV1, GEV, GLO and LN2 distributions. The EV1 and LN2 distributions are two-parameter distributions while the GLO and GEV distributions each have three-parameters.

The choice of distributions used for this study was guided by the findings in the FSU Report (September, 2009). In the case of 2-parameter distributions, the FSU Work Package 2.2 report states (Section 4.2, page 40) *"It can be deduced from the linear patterns that Irish flood data are more likely to be distributed as EV1 or LN2 rather than Logistic distribution (LO) among 2-parameter distributions"*. Therefore the elimination of LO as a 2-parameter distribution is robustly based on a study of all relevant Irish data. Also, FSU concentrated on GEV and GLO from among the available 3-parameter distributions. The lack of emphasis on LN3 by FSU was possibly based on the L-kurtosis vs. L-skewness moment ratio diagram (FSU WP 2.2 Report, Figure 3.10, page 30) and that one could be

used as a surrogate for the other. Then, because of the overwhelmingly central role, traditionally played by GEV in flood frequency analysis, the FSU decided to base its analysis using the GEV rather than LN3. The same reasoning was adopted for the present study.

Based on visual inspections of the probability plots of all 92 AMAX series, it was found that the three-parameter distributions (GLO and GEV) provide better fits to the majority of the 92 AMAX series. For the GLO distribution, out of 92 frequency curves, 80 showed concave upward shape, 5 concave downward and 7 straight lines. For the GEV distribution, 35 showed concave upward shape, 41 showed concave downward and 16 are of straight line type. Both the GLO and GEV distributions fit equally well to the observed AMAX series for Tay River at Fox Castle. Table 4.4 presents the summary results of the visual assessments of the probability plots for all 92 AMAX series. It should be noted here that one reason for the change of concavity (upward and downward) shapes seen in GEV and GLO is the difference in abscissa used in the probability plots i.e.  $EV1y = -\ln\{-\ln(1-1/T)\}$  for the GEV distribution and  $GLOy = -\ln\{1/(T-1)\}$  for the GLO distribution.

**Table 4.4: Summary results of probability plots assessments (EV1, GEV & GLO distributions) for all 92 AMAX series**

Distrib ution	No. distribution in each quality ranks (1, 2 & 3)			Fitted line type
	Rank 1 (very good)	Rank 2 (good)	Rank 3 (fair)	
EV1	18	12	62	All straight line
LN2	18	33	41	All concave upward (At Log n scale)
GEV	20	56	16	16 – straight line (GEV type I) 35 – concave upward (GEV Type II) 41 – concave downward GEV Type III)
GLO	54	24	14	7 – straight line, 80 – concave upward & 5 – concave downward

A study carried out in University College Dublin (UCD) by S. Ahilan et al. (2012) on 143 stations countrywide in Ireland found that the AMAX series of the majority of hydrometric stations located in the Eastern and South Eastern regions follow the GEV Type III distribution.

## 4.5 GROWTH CURVE ESTIMATION POINTS

In order to estimate the peak design flows for each of the 47 HEPs located on the modelled watercourses in HA17 using the 'index-flood' method (FEH, 1999; FSU, 2009), growth curves for each

of the HEPs are required. The selection of the HEPs was initially derived in accordance with the project brief and further categorised and developed based on the hydraulic model conceptualisation of the modelled watercourses within each of the AFAs. For the integration of hydrological input to the hydraulic model and also for the calibration and verification of the hydraulic models the HEPs were identified at the following locations on the modelled watercourses:

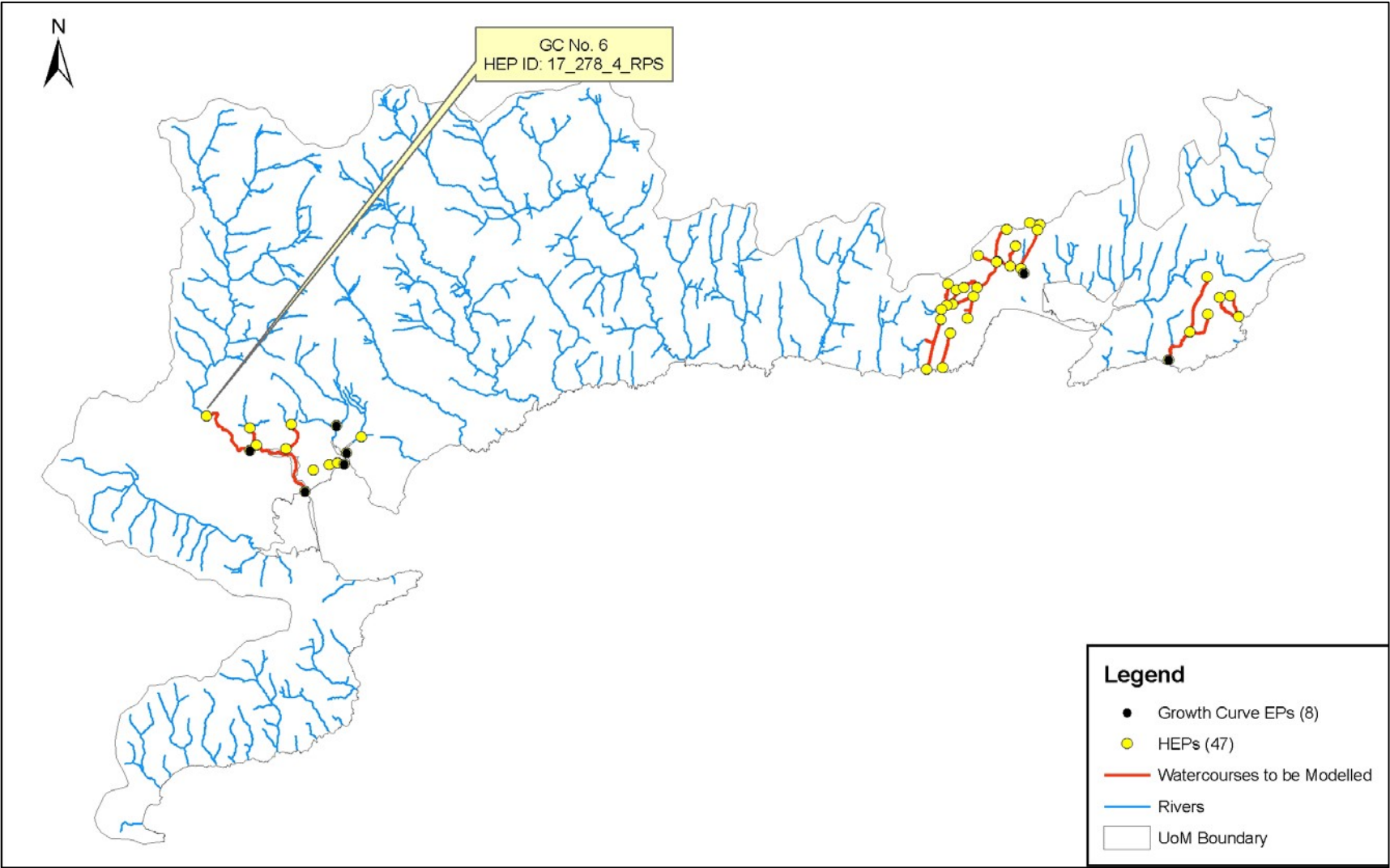
- HEPs at the upstream limit of model,
- HEPs where tributaries enter the modelled channels,
- HEPs at gauging stations on modelled channels (if present),
- HEPs at intermediate points on the modelled channels (if required), and
- HEPs at downstream limit of the model.

The details of the selection process for the HEPs are discussed in the HA17 Inception Report (Section 5.3). Table 4.5 presents a summary of the catchment characteristics associated with the HEPs in HA17. The catchment areas vary from almost zero (at the top of modelled tributaries) to 108.44 km<sup>2</sup>. The SAAR values range from 875 to 1450 mm while the BFI values vary from 0.476 to 0.704.

**Table 4.5: Summary of the catchment characteristics associated with HA17 HEPs**

<b>Catchment descriptors</b>	<b>Minimum</b>	<b>Maximum</b>	<b>Mean</b>	<b>Median</b>
AREA (km <sup>2</sup> )	0.003	108.44	8.15	0.88
SAAR (mm)	874.77	1449.67	1040.90	956.15
BFI	0.476	0.704	0.617	0.610

Based on the similarity of the catchment characteristics of these HEPs with the selected gauging sites located within the pooling region, growth curves for all HEPs with areas greater than 5 km<sup>2</sup> were estimated. Almost 95% of the selected gauging sites in the pooled region have catchment areas more than 5 km<sup>2</sup>. Therefore, the pooling groups for the HEPs with catchment areas less than 5 km<sup>2</sup> would not be the homogeneous groups and therefore the errors in the estimated growth curves would be larger. Based on these considerations, 8 HEPs (out of 47) were initially selected as points for the estimation of growth curves within HA17. Figure 4.6 shows the spatial distribution of all 47 HEPs on the modelled watercourses in HA17 with the above mentioned 8 HEPs shown in a different colour.



**Figure 4.6: Spatial distribution of the HEPs on the modelled watercourses in HA17**

Note: Refer to Section 4.7.3 for reference to GC No.6 as annotated

## 4.6 POOLING REGION AND GROUP FOR GROWTH CURVE ESTIMATION

### 4.6.1 Pooling Region

Based on the similarity of climatic characteristics, it was decided that the AMAX series from both the Eastern and South-eastern CFRAM study areas and also from the Hydrometric area 06 (HA06 – Newry, Fane, Glyde and Dee) would be pooled to form a pooling group for growth curve estimation for HA17. (The similarity in the hydrological and physiographic characteristics was taken into account in the dij value calculation when records were pooled from the selected pooling region). The pooling region for this study therefore covers the eastern and south-eastern parts of Ireland. Figure 4.1 illustrates the extent of the pooling region. A summary of the statistical properties of all AMAX series and their associated catchment characteristics is presented in Table 4.3 and 4.2 respectively. The values of AREA, SAAR and BFI encountered in the subject HEPs are summarised by their minimum, maximum, mean and median values in Table 4.5.

Comparison of these with the histograms of AREA, SAAR and BFI for the 92 stations selected for pooling purposes (Figure 4.2 to Figure 4.4) show a good overlap, which indicates that the 92 stations provide good coverage for the range of catchments encountered in the HEPs in HA17.

### 4.6.2 Pooling Group

Pooling groups can be formed on the basis of geographical proximity to the subject site. However in the UK FEH study (1999) it was found that such pooling groups were less homogeneous than those formed by Region of Influence (ROI) approach of the type proposed by Burn (1990). The ROI approach selects stations, which are nearest to the subject site in catchment descriptor space, to form the pooling group for that subject site. The FSU approach uses a distance measure in terms of three catchment descriptors of AREA, SAAR and BFI to form a pooling group. The recommended distance measure in the FSU studies is:

$$d_{ij} = \sqrt{1.7 \left( \frac{\ln AREA_i - \ln AREA_j}{\sigma_{\ln AREA}} \right)^2 + \left( \frac{\ln SAAR_i - \ln SAAR_j}{\sigma_{\ln SAAR}} \right)^2 + 0.2 \left( \frac{BFI_i - BFI_j}{\sigma_{BFI}} \right)^2} \quad (4.1)$$

Where i is the subject site and j=1,2,...M are the donor sites.

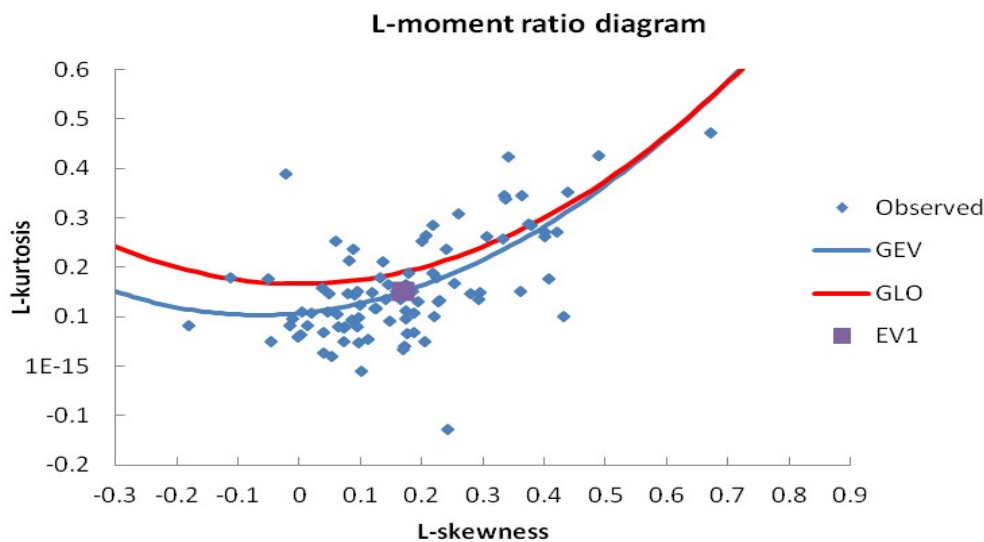
In this study, the pooling group was formed based on the above distance measure. The size of the pooling group was determined based on the FEH recommended 5T rule (i.e. the total number of station-years of data to be included when estimating the T-year flood should be at least 5T). The donor sites associated with this pooling group size were selected based on the lowest distance measures among the available gauging sites in the pooling region. Individual pooling groups were developed and growth curves estimated for every HEP. However, the estimated pooled growth factors/curves were generalised further based on a range of catchment sizes as discussed later in Section 4.8.2.

## 4.7 GROWTH CURVE ESTIMATION

### 4.7.1 Choice of Growth Curve Distributions

In the ‘index-flood’ method one of the major assumptions is that the frequency distributions at different sites in the pooled group are identical apart from a scale factor, which is the median flow ( $Q_{med}$ ).

As discussed in Section 4.4, the three-parameter GEV and GLO distributions were found to be better suited distribution for most of the 92 AMAX series than the two-parameter distributions. Furthermore, it can be seen from the L-moment ratio diagram for these 92 AMAX series as shown in Figure 4.7 that the GEV distribution provides better fits than the GLO distribution, since the theoretical values of the GEV distribution’s L-Skewness and L-Kurtosis pass centrally through the observed L-moments ratios of the 92 AMAX series.



**Figure 4.7: L-moment ratio diagram (L-skewness versus L-kurtosis)**

Based on the above, the GEV distribution can be adopted as the best candidate distribution for the regional growth curves for the subject river catchments in HA17. However, since the probability plots show that the GLO distribution is also suitable, this distribution is also considered as a candidate distribution for the regional growth curve estimation. Although the two-parameter distributions exhibit more bias in the regional flood frequency estimates as compared to the three-parameter distributions, the two-parameter EV1 distribution is also used in the growth curve estimation process for comparison purposes and to replace the GEV or GLO growth curve when the shape displayed by either of these two distributions is concave downward in order to avoid potential underestimation of extreme event growth factors.

### 4.7.2 Estimation of Growth Curves

The algebraic equations of the EV1, GEV and GLO growth curves and associated parameters are given below:



**EV1 distribution:**

$$\text{Growth Curve: } x_T = 1 + \beta (\ln(\ln 2) - \ln(-\ln(1-1/T))) \quad (4.2)$$

$$\text{Parameter: } \beta = \frac{t_2}{\ln 2 - t_2 [\gamma + \ln(\ln 2)]} \quad (4.3)$$

where,  $t_2$  is the L-coefficient of variation (L-CV) and  $\gamma$  is Euler's constant = 0.5772.

**GEV distribution:**

$$\text{Growth Curve: } x_T = 1 + \frac{\beta}{k} \left[ \left( \ln 2 \right)^k - \left( \ln \frac{T}{T-1} \right)^k \right], \quad k \neq 0 \quad (4.4)$$

The parameters  $k$  and  $\beta$  are estimated from sample  $t_2$ =L-CV and sample  $t_3$ =L-skewness as follows:  
[Hosking & Wallis (1997, p.196)]

$$k = 7.8590c + 2.9554c^2 \text{ where } c = \frac{2}{3+t_3} - \frac{\ln 2}{\ln 3} \quad (4.5)$$

$$\beta = \frac{kt_3}{t_2 \left( \Gamma(1+k) - (\ln 2)^k \right) + \Gamma(1+k)(1-2^{-k})} \quad (4.6)$$

**GLO distribution:**

$$\text{Growth Curve: } x_T = 1 + \frac{\beta}{k} \left( 1 - \{T-1\}^{-k} \right), \quad k \neq 0 \quad (4.7)$$

The parameters  $k$  and  $\beta$  are estimated from sample  $t_2$ =L-CV and sample  $t_3$ =L-skewness as follows  
[Hosking & Wallis (1997, p.197)]:

$$k = -t_3 \text{ and } \beta = \frac{kt_2 \sin(\pi k)}{k\pi(k+t_2) - t_2 \sin(\pi k)} \quad (4.8)$$

The pooled regional values of the  $t_2$  (L-CV) and  $t_3$  (L-skewness) have been estimated as the weighted average values of corresponding at-site sample values weighted by the at-site record lengths. These values were equated to the expressions for these quantities written in terms of the distribution's unknown parameters as given above and the resulting equations are solved for the unknown parameters.

### 4.7.3 Examination of Growth Curve Shape

Growth curves for all of the selected eight Growth Curve (GC) EPs (Estimation Points) for a range of AEPs were estimated in accordance with the above methodologies. An examination of the derived shapes of the growth curves showed that, because of the fixed shape distribution, the EV1 growth curves are of straight-line type for all eight GC EPs, while in the GEV and GLO distribution cases growth curves take either the concave upwards (upward bend) or concave downwards (downward bend) shapes based on the skewness of the pooled group. In the GEV distribution case, five showed concave upward, one concave downward and two showed straight lines, while in the GLO distribution case, all eight curves showed concave upward shape (Table 4.6).

**Table 4.6: Growth curves shape summary**

Distribution	Growth Curve Shape
EV1	All straight lines
GEV	5 – concave upward 1 – concave downward 2 – straight line
GLO	All concave upward

An assessment of the suitability of the above three growth curve distributions was carried out by examining the suitability of these distributions in fitting the AMAX series in the pooling groups associated with all eight HEPs. In other words, for a particular HEP, the pooled growth curves, based on EV1, GEV and GLO, were superimposed on the standardised probability plots of the AMAX series which form the pooling group (typically 10 to 12 such series). A visual comparison of the suitability of the growth curves was made and recorded, as in the example for GC EP No. 6. This was selected to illustrate the composition of one pooling group.

In estimating the pooled growth curve for GC EP No.6, 535 station-years of records from 15 sites were pooled. Figure 4.6 shows the location of this HEP. Table 4.7 shows the catchment characteristics, statistical properties and estimated distance measures for each of the sites from the subject HEP.

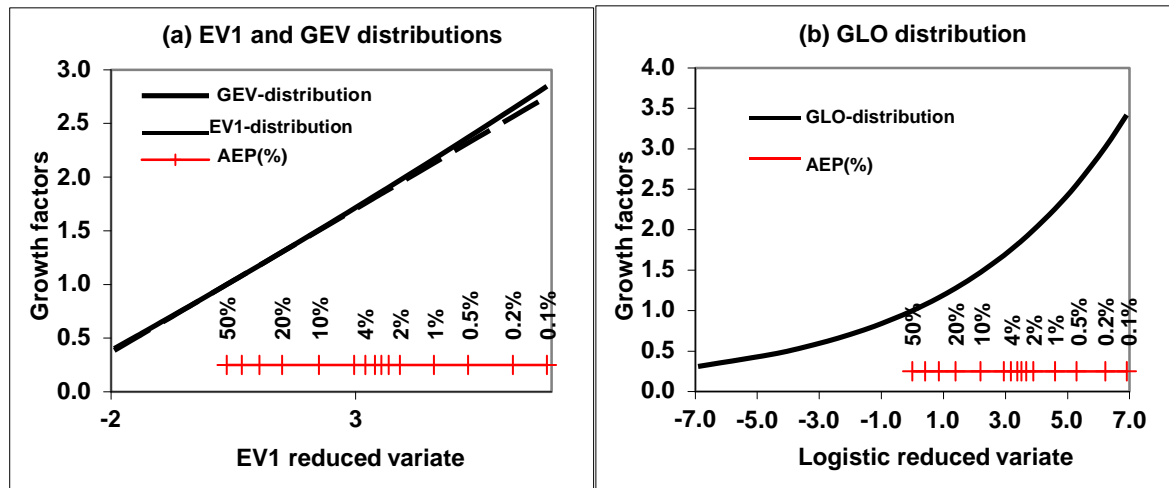
**Table 4.7: Catchment descriptors for all pooled sites for growth curve 6**

Hydrometric stations	Record length (years)	AREA (km <sup>2</sup> )	SAAR (mm)	BFI	Qmean (m <sup>3</sup> /s)	Specific Qmean (m <sup>3</sup> /s/km <sup>2</sup> )	L-CV	L-skew	L-kur	d <sub>ij</sub>
16013	45	93.58	1471.29	0.539	88.45	0.945	0.229	0.186	0.152	0.249
15021	11	67.05	1358.56	0.651	24.42	0.364	0.162	0.438	0.351	0.564
10002	52	230.89	1530.19	0.538	92.61	0.401	0.231	0.338	0.337	0.965
16012	46	229.63	1320.79	0.628	62.34	0.271	0.241	0.408	0.177	1.071
16007	56	273.26	1330.55	0.578	80.45	0.294	0.207	0.039	0.027	1.147
12013	35	204.39	1383.48	0.743	44.47	0.218	0.146	0.037	0.157	1.200
16005	35	84.00	1153.57	0.560	22.99	0.274	0.096	0.166	0.136	1.337
10028	22	202.92	1396.92	0.788	66.84	0.329	0.272	0.421	0.271	1.365
10004	14	30.57	1700.39	0.436	38.48	1.259	0.232	0.488	0.426	1.448
16003	56	243.20	1192.01	0.550	30.94	0.127	0.093	0.220	0.100	1.482
14033	10	78.89	1145.22	0.454	20.84	0.264	0.052	0.095	0.080	1.519
16006	38	75.80	1115.82	0.587	29.46	0.389	0.215	0.072	0.049	1.530
14003	27	206.73	1160.51	0.532	33.71	0.163	0.112	0.046	0.109	1.541
15007	35	339.76	1123.04	0.594	46.53	0.137	0.098	-0.112	0.180	1.926
06012	53	162.80	1046.24	0.680	15.27	0.094	0.169	0.173	0.112	2.065
<b>Subject site (Growth Curve EP-6)</b>	-	<b>81</b>	<b>1449.67</b>	<b>0.577</b>	-	-	<b>0.175*</b>	<b>0.182*</b>	-	-

\*Pooled regional values

It can be seen from the above table that the subject site's catchment characteristics are well placed within the pooled sites' catchment descriptor space. The subject site has an upstream catchment area of 81 km<sup>2</sup>, SAAR and BFI values of 1449.67 mm and 0.577 respectively which are located approximately at the median locations of the pooled sites' corresponding values.

The estimated pooled average L-CV and L-Skewness are 0.175 and 0.182 respectively. This suggests that the pooled growth curve would follow a distribution which has L-Skewness greater than that of the EV1 distribution (0.167). Figure 4.8 shows the estimated EV1, GEV and GLO growth curves for growth curve No. 6. The GEV growth curve is a slightly concave downward shaped curve while the GLO one is a moderately concave upward shaped curve.



**Figure 4.8: Pooled Growth Curve 6 - (a) EV1 and GEV distributions; (b) GLO distributions**

An assessment of the at-site GEV and GLO growth curves was carried out through a visual inspection of their individual probability plots. A summary of this assessment is provided Table 4.8.

**Table 4.8: Frequency curve shapes of the individual site's AMAX series associated with the pooled group No. 6**

Hydrometric stations	Individual at-site growth curves		
	GEV (EV1y Plot)	GLO (Loy Plot)	Comparison of performances (visual)
16013	Straight line	Moderate concave upward	GEV fits slightly better
15021	Mild concave upward	Mild concave upward	GLO fits slightly better
10002	Mild concave upward	Moderate concave upward	Both fit equally well to the observed records
16012	Mild concave upward	Moderate concave upward	Both fit equally well to the observed records
16007	Mild concave downward	Mild concave upward	Both fit equally well to the observed records
12013	Mild concave downward	Mild concave upward	GLO fits slightly better
16005	Straight line	Mild concave upward	Both fit equally well to the observed records
10028	Mild concave upward	Moderate concave upward	Both fit equally well to the observed records
10004	Mild concave downward	Mild concave upward	Both fit equally well to the observed records
16003	Mild concave upward	Mild concave upward	Both fit equally well to the observed records
14033	Mild concave downward	Mild concave upward	GLO fits slightly better
16006	Mild concave downward	Mild concave upward	Both fit equally well to the observed records
14003	Mild concave downward	Mild concave upward	GLO fits slightly better
15007	Moderate concave upward	Mild concave upward	GLO fits slightly better
06012	Mild concave upward	Moderate concave upward	Both fit equally well to the observed records

This assessment shows that both the GEV and GLO distributions fit the observed at-site records quite well at all 15 sites with a slightly better performance by the GLO distribution. In the case of the GEV distribution six sites showed concave downward shaped curves (mild to moderate), seven concave upward and two sites showed straight line. While in the GLO distribution case, all 15 sites showed concave upward shaped curves. This suggests that the shape of the pooled growth curves in the case of GLO distribution can be expected to be concave upward.

Table 4.9 shows the estimated growth factors for a range of AEPs for Growth Curve No. 6. The estimated 1% AEP growth factors for the EV1, GEV and GLO distributions are 2.132, 2.169 and 2.258 respectively.

**Table 4.9: Estimated growth factors for Growth Curve No. 6**

AEP (%)	EV1	GEV	GLO
50	1.000	1.000	1.000
20	1.303	1.304	1.276
10	1.504	1.509	1.473
5	1.696	1.708	1.682
2	1.945	1.970	1.991
1	2.132	2.169	2.258
0.5	2.318	2.370	2.558
0.1	2.749	2.846	3.418

#### 4.7.4 Recommended Growth Curve Distribution for the River Catchments in HA17

The following factors were considered to select an appropriate growth curve distribution for the subject river catchments within HA17:

- I. Suitability of a distribution in fitting the individual at-site records,
- II. No. of distribution parameters, and
- III. Shape of the pooled growth curve

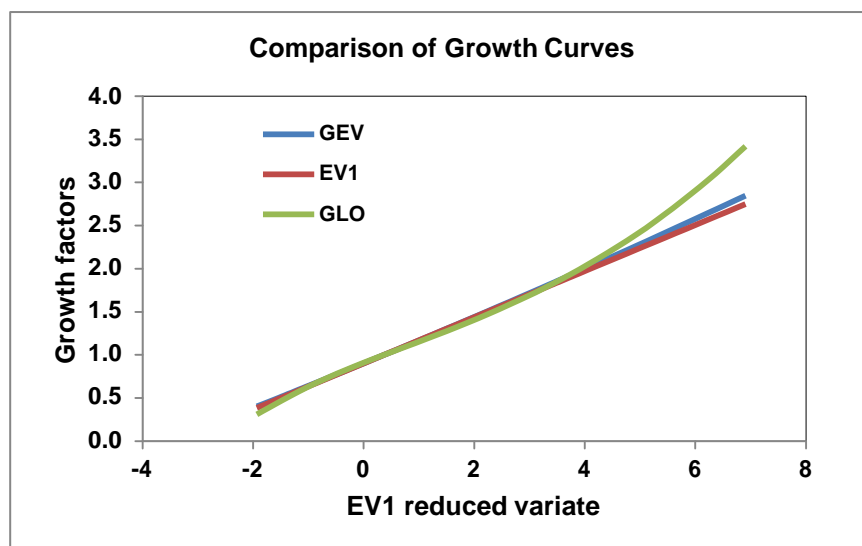
Visual examination of the at-site frequency curves for all 92 gauging sites showed that the AMAX series for most of these sites can be described slightly better by the GLO distribution than by the EV1 and GEV distributions.

The number of distribution parameters also plays an important role in deriving an appropriate growth curve. The fixed skewness two-parameter distributions generally suffer from large biases, particularly at the upper tail of the distribution. The three-parameter distributions, in contrast, suffer from larger standard error though they are less biased. However this standard error is generally reduced by the pooled estimation process. The use of two-parameter distributions such as the Gumbel distribution is not therefore recommended in regional frequency analysis (Hosking and Wallis, 1996). The use of a two-parameter distribution is beneficial only if the investigator has complete confidence that the 'at site'

distribution's L-Skewness and L-kurtosis are close to those of the frequency distributions. As discussed in Section 4.7.1, the L-CV and L-Skewness of most of the sites in the Pooling Region differ from those of the theoretical values of the EV1 distribution. This suggests that a three-parameter distribution would be more appropriate to describe the growth curves for the subject watercourses within HA17.

The shape of the growth curve also plays an important role in the design and operation of the flood management scheme for a river catchment. It is generally not considered appropriate to have a growth curve with a concave downward shape. In the HA17 river catchments all eight GLO growth curves are of concave upward shape, in the GEV distribution case two are concave upward shape and one is a straight line.

The estimated 1%-AEP GLO growth factor is slightly greater than the GEV growth factor, for all growth curves by 0.1 to 5% (see growth curve No. 6). This is largely due to the concavity noted above. Figure 4.9 shows a comparison of the GEV, GLO and EV1 growth curves for growth curve No. 6, all plotted in the EV1 probability plot.



**Figure 4.9: Comparison of EV1, GEV and GLO growth curves on the EV1-y probability plot (Growth Curve No. 6)**

Based on the above it is recommended to adopt the GLO distribution derived concave upward shape growth curve for the subject rivers catchments in HA17. Figure 4.10 shows the estimated eight GLO growth curves (for 8 GC EPs) for the HA17 river catchments.

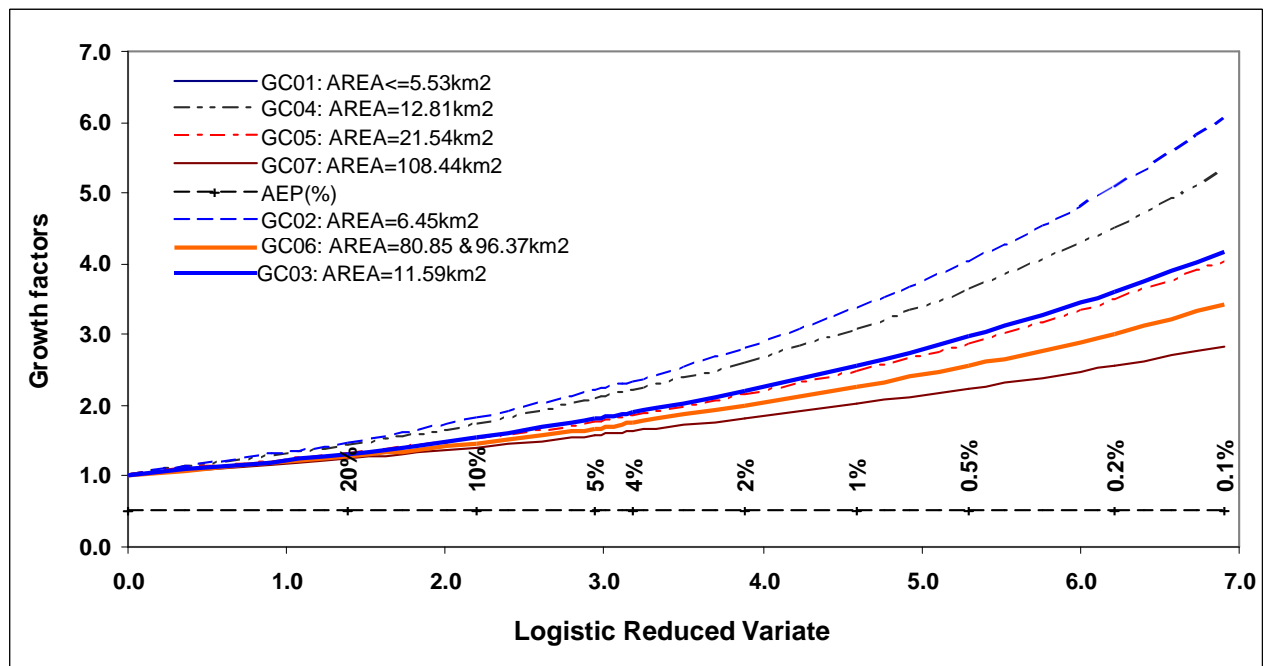


Figure 4.10: GLO growth curves for HA17 Rivers Catchments

## 4.8 RATIONALISATION OF GROWTH CURVES

### 4.8.1 Relationship of Growth Factors with Catchment Characteristics

An examination of the relationship of the estimated growth factors with the catchment characteristics (AREA, SAAR & BFI) showed that growth factors generally increase with a decrease in catchment sizes as can be seen in Table 4.10 and Figure 4.10. This can be attributed to the smaller upland catchment areas where catchment response time is shorter and where no flow attenuation is available. For the larger catchments flow attenuation is generally provided by lakes and wider downstream channels. No such particular patterns in the relationships of the growth factors with the SAAR and BFI values were found.

Table 4.10: Estimated GLO growth factors for 8 Growth Curve EPs in HA17

AEP (%)	HEP01 (5.53km <sup>2</sup> )	HEP02 (6.45km <sup>2</sup> )	HEP03 (11.59km <sup>2</sup> )	HEP04 (12.81km <sup>2</sup> )	HEP05 (21.54km <sup>2</sup> )	HEP06 (80.85km <sup>2</sup> )	HEP07 (96.37km <sup>2</sup> )	HEP08 (108.44km <sup>2</sup> )
50	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
20	1.382	1.456	1.324	1.416	1.301	1.276	1.276	1.238
10	1.669	1.805	1.562	1.728	1.525	1.473	1.473	1.401
5	1.987	2.195	1.822	2.071	1.770	1.682	1.682	1.570
4	2.098	2.332	1.912	2.191	1.855	1.753	1.753	1.626
2	2.478	2.806	2.217	2.600	2.145	1.991	1.991	1.811
1	2.920	3.362	2.566	3.074	2.478	2.258	2.258	2.012
0.5	3.437	4.018	2.968	3.625	2.865	2.558	2.558	2.233
0.2	4.258	5.075	3.597	4.500	3.473	3.017	3.017	2.561
0.1	5.007	6.050	4.161	5.293	4.022	3.418	3.418	2.838



Because of the small number of HEPs in HA17, no further rationalisation of growth curves based on relationship with catchment size was considered. In this case, the estimated individual GLO growth curve for each HEP with a catchment area greater than  $5\text{km}^2$  was recommended as the design growth curve. For all HEPs with catchment areas less than  $5\text{km}^2$ , it is recommended to use the estimated growth factors associated with the catchment area of  $5.53\text{km}^2$  as shown in Table 4.11. In HA17, 39 out of 47 HEPs have catchment areas less than  $5\text{km}^2$ . The estimated growth factors for Growth Curve EPs No. 6 & 7 were found to be similar. For these HEPs, one growth curve is therefore recommended (see Table 4.11).

**Table 4.11: Growth Curve types**

GC No.	Catchment size range	Growth curve type / estimation type
1	$\text{AREA} \leq 5.53\text{km}^2$	Use the estimated growth curve associated with the catchment area of $5.53\text{km}^2$
2	$\text{AREA} = 6.45\text{km}^2$	Use individual growth curve
3	$\text{AREA} = 11.59\text{km}^2$	Use individual growth curve
4	$\text{AREA} = 12.81\text{km}^2$	Use individual growth curve
5	$\text{AREA} = 21.54\text{km}^2$	Use individual growth curve
6	$\text{AREA} = 80.85 \text{ \& } 96.37\text{km}^2$	Use individual growth curve
7	$\text{AREA} = 108.44\text{km}^2$	Use individual growth curve

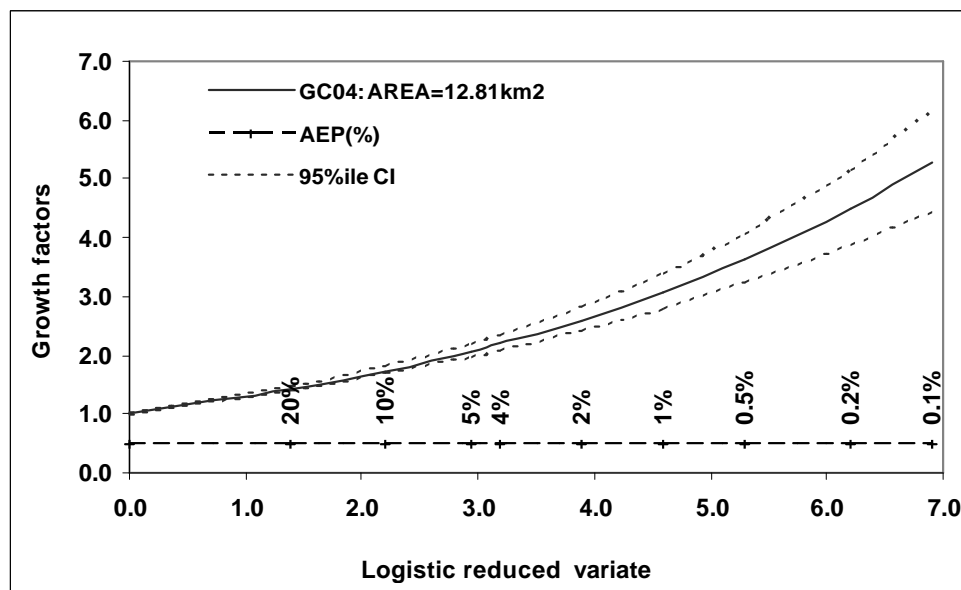
The uncertainties associated with the above growth curve estimates are expressed in terms of 95% confidence interval of these estimates and were estimated from the following relationship:

$$X_T(95\%ile) = X_T \pm 1.96 \times se(X_T) \quad (4.9)$$

The standard error (se) of the growth curves is estimated in accordance with the FSU recommended methodology. Table 4.12 presents the estimated standard errors in terms of percentage of the estimated growth factor for a range of AEPs. The upper and lower limits of the confidence interval were estimated using the above mentioned Eq. 4.9. For example, for the GC Group No. 4, the estimated 1%-AEP growth factor is 3.074 and the associated 95% upper and lower confidence limits are 3.375 and 2.773 respectively. Figure 4.11 shows the estimated growth curve along with the 95% upper and lower confidence limits for GC Group No. 4.

**Table 4.12: Estimated percentage standard errors for growth factors (X<sub>T</sub>) for a range of AEPs (source FSU Work- Package 2.2 “Frequency Analysis” Final Report – Section 13.3)**

Return periods (years)	Annual Exceedance probabilities (%)	Se (X <sub>T</sub> ) %
2	50%	0.60
5	20%	1.00
10	10%	1.80
20	5%	2.77
25	4%	3.00
50	2%	3.90
100	1%	5.00
200	0.5%	5.94
500	0.2%	7.30
1000	0.1%	8.30



**Figure 4.11: Growth Curve for GC Group No. 4 with 95% confidence limits**

#### 4.8.2 Comparison of the at-site growth curves with the pooled growth curves

The FSU programme recommended that “*in the event that the at-site estimate of Q-T relation is steeper than the pooled one then consideration will have to be given to using a combination of the at-site estimate and the pooled estimate for design flow estimation*”. However, none of the sites with available AMAX records in HA17 are located on the modelled watercourses. Therefore, no comparison of the regional estimates of growth curves could be carried out with the corresponding at-site estimate.

### 4.8.3 Growth factors for all HEPs within HA17

Table 4.13 presents the estimated growth factors for all 47 HEPs for a range of AEPs in HA17.

**Table 4.13: Growth factors for all 47 HEPs for a range of AEPs for the modelled HA17 River Catchments**

Node No.	Node ID_CFRAMS	AREA (km <sup>2</sup> )	Growth factors (X <sub>T</sub> )								
			1% AEP			0.2% AEP			0.1% AEP		
			Upper 95%ile	X <sub>T</sub>	Lower 95%ile	Upper 95%ile	X <sub>T</sub>	Lower 95%ile	Upper 95%ile	X <sub>T</sub>	Lower 95%ile
1	17_379_2_RPS	1.09	2.634	2.920	3.206	3.649	4.258	4.867	4.192	5.007	5.822
2	17_673_2_RPS	1.02	2.634	2.920	3.206	3.649	4.258	4.867	4.192	5.007	5.822
3	17_683_1	0.88	2.634	2.920	3.206	3.649	4.258	4.867	4.192	5.007	5.822
4	17_580_1	0.82	2.634	2.920	3.206	3.649	4.258	4.867	4.192	5.007	5.822
5	17_34_1	0.28	2.634	2.920	3.206	3.649	4.258	4.867	4.192	5.007	5.822
6	17_666_2_RPS	2.48	2.634	2.920	3.206	3.649	4.258	4.867	4.192	5.007	5.822
7	17_679_1	0.86	2.634	2.920	3.206	3.649	4.258	4.867	4.192	5.007	5.822
8	17_730_1	0.66	2.634	2.920	3.206	3.649	4.258	4.867	4.192	5.007	5.822
9	17_485_U	0.23	2.634	2.920	3.206	3.649	4.258	4.867	4.192	5.007	5.822
10	17_377_U	0.03	2.634	2.920	3.206	3.649	4.258	4.867	4.192	5.007	5.822
11	17_377_1	0.08	2.634	2.920	3.206	3.649	4.258	4.867	4.192	5.007	5.822
12	17_673_U	0.17	2.634	2.920	3.206	3.649	4.258	4.867	4.192	5.007	5.822
13	17_379_U	0.03	2.634	2.920	3.206	3.649	4.258	4.867	4.192	5.007	5.822
14	17_679_U	0.15	2.634	2.920	3.206	3.649	4.258	4.867	4.192	5.007	5.822
15	17_730_U	0.13	2.634	2.920	3.206	3.649	4.258	4.867	4.192	5.007	5.822
16	17_34_U	0.09	2.634	2.920	3.206	3.649	4.258	4.867	4.192	5.007	5.822
17	17_42_U	0.02	2.634	2.920	3.206	3.649	4.258	4.867	4.192	5.007	5.822
18	17_585_U	0.05	2.634	2.920	3.206	3.649	4.258	4.867	4.192	5.007	5.822
19	17_802_U	0.00	2.634	2.920	3.206	3.649	4.258	4.867	4.192	5.007	5.822
20	17_648_U	0.05	2.634	2.920	3.206	3.649	4.258	4.867	4.192	5.007	5.822
21	17_830_4_RPS	2.95	2.634	2.920	3.206	3.649	4.258	4.867	4.192	5.007	5.822
22	17_134_U	0.01	2.634	2.920	3.206	3.649	4.258	4.867	4.192	5.007	5.822
23	17_282_U	0.06	2.634	2.920	3.206	3.649	4.258	4.867	4.192	5.007	5.822
24	17_288_U	0.10	2.634	2.920	3.206	3.649	4.258	4.867	4.192	5.007	5.822
25	17_186_U	0.07	2.634	2.920	3.206	3.649	4.258	4.867	4.192	5.007	5.822
26	17010	96.37	2.037	2.258	2.479	2.585	3.017	3.449	2.862	3.418	3.974
27	17_277_1_RPS	4.51	2.634	2.920	3.206	3.649	4.258	4.867	4.192	5.007	5.822
28	17_830_1_RPS	1.52	2.634	2.920	3.206	3.649	4.258	4.867	4.192	5.007	5.822
29	17_277_3_RPS	4.76	2.634	2.920	3.206	3.649	4.258	4.867	4.192	5.007	5.822
30	17_278_4_RPS	80.85	2.037	2.258	2.479	2.585	3.017	3.449	2.862	3.418	3.974
31	17_832_2_RPS	108.44	1.815	2.012	2.209	2.195	2.561	2.927	2.376	2.838	3.300
32	17_706_1_RPS	1.02	2.634	2.920	3.206	3.649	4.258	4.867	4.192	5.007	5.822

Node No.	Node ID_CFRAMS	AREA (km <sup>2</sup> )	Growth factors ( $X_T$ )								
			1% AEP			0.2% AEP			0.1% AEP		
			Upper 95%ile	$X_T$	Lower 95%ile	Upper 95%ile	$X_T$	Lower 95%ile	Upper 95%ile	$X_T$	Lower 95%ile
33	17_823_2_RPS	12.81	2.773	3.074	3.375	3.856	4.500	5.144	4.432	5.293	6.154
34	17_134_2_RPS	1.23	2.634	2.920	3.206	3.649	4.258	4.867	4.192	5.007	5.822
35	17_266_3_RPS	6.45	3.033	3.362	3.691	4.349	5.075	5.801	5.066	6.050	7.034
36	17_641_4_RPS	2.15	2.634	2.920	3.206	3.649	4.258	4.867	4.192	5.007	5.822
37	17_648_1	0.88	2.634	2.920	3.206	3.649	4.258	4.867	4.192	5.007	5.822
38	17_288_1	0.69	2.634	2.920	3.206	3.649	4.258	4.867	4.192	5.007	5.822
39	17_282_2_RPS	2.07	2.634	2.920	3.206	3.649	4.258	4.867	4.192	5.007	5.822
40	17_1001_Inter1	1.47	2.634	2.920	3.206	3.649	4.258	4.867	4.192	5.007	5.822
41	17_1001_Inter2	1.67	2.634	2.920	3.206	3.649	4.258	4.867	4.192	5.007	5.822
42	17_303_1_RPS	11.59	2.315	2.566	2.817	3.082	3.597	4.112	3.484	4.161	4.838
43	17_645_1	3.22	2.634	2.920	3.206	3.649	4.258	4.867	4.192	5.007	5.822
44	17_645_2_RPS	5.53	2.634	2.920	3.206	3.649	4.258	4.867	4.192	5.007	5.822
45	17_1001_US	0.25	2.634	2.920	3.206	3.649	4.258	4.867	4.192	5.007	5.822
46	17_1001_Trib	1.73	2.634	2.920	3.206	3.649	4.258	4.867	4.192	5.007	5.822
47	17_303_DS	21.54	2.235	2.478	2.721	2.976	3.473	3.970	3.368	4.022	4.676

The design flood flows for any required AEP will be calculated by multiplying the Index Flood,  $Q_{med}$  of each HEP by the above estimated relevant growth factors. Since HEPs in HA17 are ungauged,  $Q_{med}$  will be estimated from the FSU and IH 124 recommended catchment descriptors based methodologies (refer to Chapters 2 and 3).

It should be noted here that any uncertainties in the design flood estimates obtained from the index-flood method generally result from the uncertainties associated with both the index-flood ( $Q_{med}$ ) and growth factor estimates. The uncertainties in the growth factor estimates can result both from the sampling variability and misspecification of the growth curve distribution. The sampling error is considered to be small due to the larger record lengths (pooled records) used in the estimation process.

Furthermore, it should also be noted here that, any allowances for future climate change in the design flood flow estimate should be applied to the median flow estimates. Any effects of the climate change on the growth curves are expected to be minimal.

## 4.9 COMPARISON WITH FSR GROWTH FACTORS

A comparison of the estimated growth factors for the subject rivers catchments within HA17 was carried out with the FSR growth factors for a range of AEPs as can be seen in Table 4.14. All growth curves were indexed to the median annual maximum flows ( $Q_{med}$ ).

**Table 4.14: Study area growth factors compared with FSR growth factors**

AEP (%)	50%	20%	10%	4%	2%	1%	0.5%	0.2%	0.1%
HA17 Rivers catchments	1.000	1.238 to 1.485	1.401 to 1.805	1.626 to 2.332	1.811 to 2.806	2.012 to 3.362	2.233 to 4.018	2.561 to 5.075	2.838 to 6.050
Average of HA17	1.000	1.374	1.654	2.071	2.440	2.868	3.368	4.161	4.883
FSR	1.000	1.260	1.450	1.630	1.870	2.060	2.620	2.530	2.750

It can be seen from the above table that the study area growth factors (average values) are higher than the FSR growth factors. These higher growth factors for the HA17 river catchments can be attributed to the steeper nature of the smaller river catchments and the pooling region from which the AMAX records were pooled.

## 4.10 GROWTH CURVE DEVELOPMENT SUMMARY

Growth curves for all HEPs were estimated from the regional flood frequency analysis technique as recommended in the FEH, FSU and FSR studies (Region of Influence Approach).

AMAX records from the 92 hydrometric stations located in the Eastern and South Eastern Region of Ireland were pooled for estimating the pooled growth curves for 47 HEPs. The selection of this pooling region was based on the similarity of catchment characteristics both in terms of climatic and physiographic characteristics. The size of a pooling group associated with each of the HEPs was determined based on the FEH recommended 5T rule (with a minimum of 500 station-years AMAX series for each pooled growth curve). The pooling process was based on the FSU recommended catchment characteristics based (AREA, SAAR and BFI) distance measures between the subject and donor sites.

The statistical distribution suitable for a pooled growth curve was determined based on a number of factors such as - the suitability of this distribution for fitting the contributory stations' at-site AMAX series, the number of distribution parameters and shape of the growth curves (concave upward or concave downward). Four flood like distributions namely, the EV1, LN2, GEV and GLO distributions were considered. The three-parameter GLO distribution was found to be the best suited distribution in all respects and therefore was chosen as the growth curve distribution for all HEPs in HA17.

It was found that growth factors generally increase with a decrease in catchment area. However, because of the small number of HEPs in HA17, no rationalisation of growth curves based on relationship with catchment size was considered for the HA17 catchments. The estimated individual GLO growth curve for each HEP with a catchment area greater than  $5\text{km}^2$  was recommended for use as the design growth curve. For all HEPs with catchment areas less than  $5\text{km}^2$ , it is recommended to use the estimated growth factors associated with the catchment area of  $5.53\text{ km}^2$  as shown in Table 5.10. In HA17, out of 47 HEPs, 39 HEPs have catchment areas less than  $5\text{km}^2$ .

The estimated 1% AEP growth factors for the subject rivers catchments in HA17 vary from 2.012 to 3.362 depending on the catchment size. Growth factors for the smaller catchments are larger than those of the larger catchments.

## 5 DESIGN FLOWS

### 5.1 DESIGN FLOW HYDROGRAPHS

Following estimation of the Index Flood Flow ( $Q_{med}$ ) and growth factors for each HEP it is possible to estimate the peak design flows for a range of Annual Exceedance Probabilities (AEPs). All of the design flows which will be used for hydraulic modelling input are detailed in Appendix B. The final component of estimating the fluvial design flows is to ascertain the profile of the design flow hydrograph for each HEP, i.e. the profile of the flow over time as a flood event rises from its base flow to achieve the peak design flow (rising limb) and then as the flood flow rate decreases and the watercourse returns to more normal flows (recession limb). As discussed in Chapter 2 of this report the methodology for this study has been developed further since production of the Inception Report and as such two methodologies have been used within HA17 to derive the design flow hydrograph shapes (widths) such that these can be applied to a range of design events:

1. FSU Hydrograph Shape generation tool (developed from FSU WP 3.1) for all HEPs with the exception of 2 (below);
2. FSSR 16 Unit Hydrograph method for small (catchment less than  $5 \text{ km}^2$ ) where no suitable pivotal site is available.

#### 5.1.1 FSU Hydrograph Shape Generator

The Hydrograph Shape Generator tool developed as an output from FSU WP 3.1 was used to derive the design hydrograph for HEPs in HA17. The Hydrograph Shape Generator Tool is an Excel spreadsheet containing a library of parametric, semi-dimensionless hydrograph shapes derived from gauge records of pivotal sites using the HWA software previously discussed. Based on hydrological similarity, a pivotal site hydrograph is 'borrowed' and applied at the subject site (in this case the CFRAMS HEP) based on catchment descriptors. One potential issue with the use of the Hydrograph Shape Generator tool is the lack of small catchments from which suitably short hydrographs are available. This, along with overly long receding limbs on hydrographs, was particularly noticeable in earlier versions of the software but is much improved with the addition of further pivotal sites to bring the number within the library up to 145. Within HA17 the latest version of the software (version 5) was found to provide suitable hydrograph shapes for 10 of the HEPs.

#### 5.1.2 FSSR 16 Unit Hydrograph Method

In many instances it was found that Pivotal Sites could not be found which were sufficiently hydrologically similar to the subject catchment such that hydrograph shape parameters could be borrowed and hydrograph generated as per Section 5.1.1. This was particularly the case for some of the very small sub-catchments e.g. the small HPWs affecting the Tramore Environs and Dunmore East AFAs. The FSSR 16 Unit Hydrograph method was used for these catchments whereby semi dimensionless hydrographs were derived with the same time-step as used for the other hydrographs

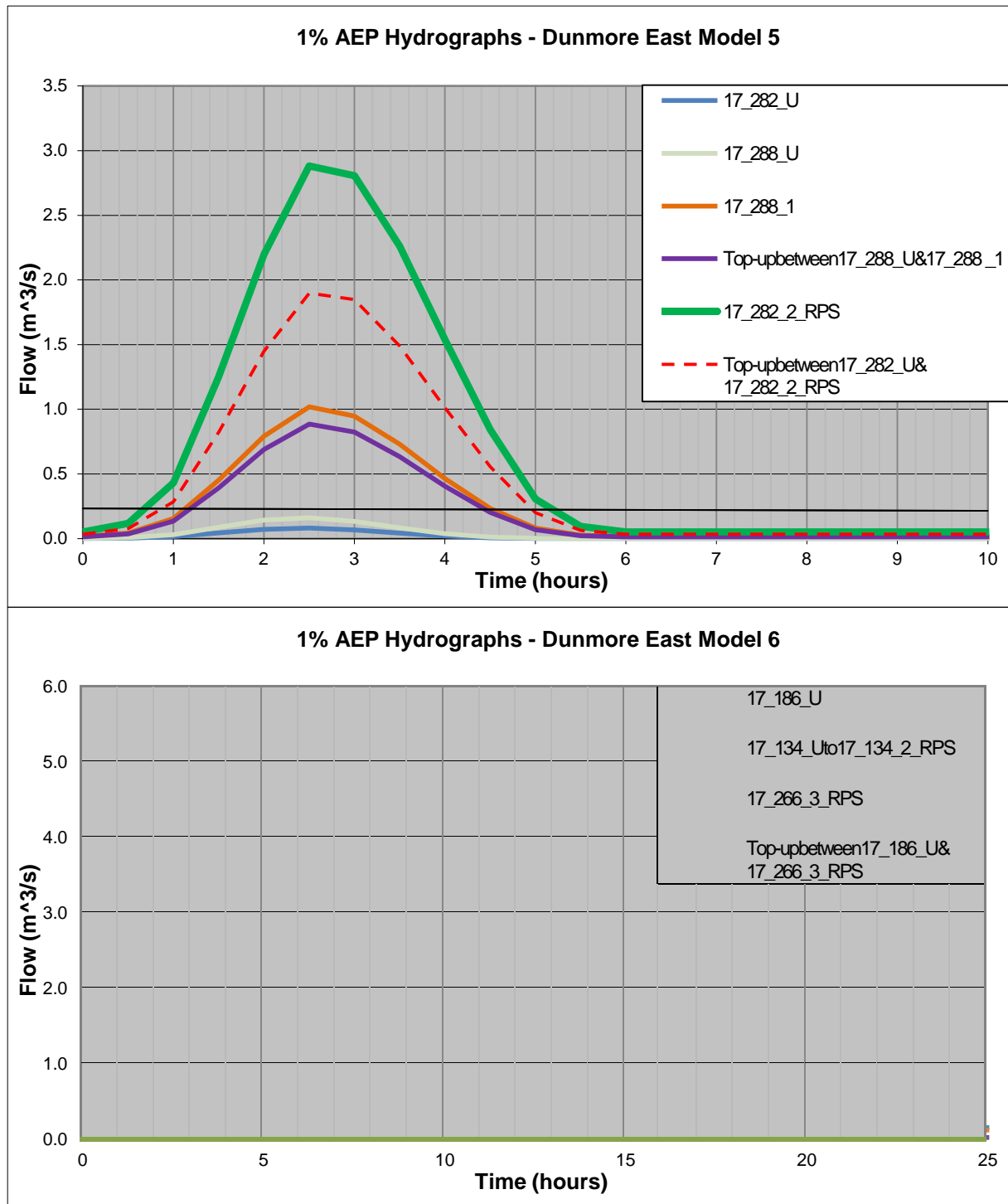


within the model using the ISIS FSSR 16 UH tool. The methodology followed to derive the FSSR 16 semi dimensionless hydrograph for a subject catchment is summarised below:

1. Time to Peak of the 1 hour unit hydrograph estimated from FSU PCDs (area, MSL, S1085, SAAR & URBEXT) and adjusted for time step
2. Design storm duration estimated as a function of SAAR and the estimated time to peak
3. Areal reduction factor calculated as a function of design storm duration and catchment area.
4. Catchment Wetness Index calculated as a function of SAAR.
5. Soil index calculated using FSR Winter Rain Acceptance Potential soil mapping
6. Standard Percentage Runoff (SPR) calculated as a function of the soil types within the subject catchment
7. Rainfall characteristics for the subject catchment derived from FSU DDF gridded outputs (M5-2D & M5-25D) and FSR maps (Jenkinson's Ratio  $r$ )

The outputs from steps 2 to 7 were input to the ISIS FSSR 16 boundary unit module to produce a semi dimensionless hydrograph (fitted to a peak of 1) based on Unit Hydrograph principles which was then scaled to the various design peak flows

Following the application of these methodologies hydrographs were available for application within the hydraulic model. Using the small tributaries in Dunmore East as an example (refer to Figure 3.5, Models 5 and 6), the input / check hydrographs at each HEP are shown for the 1% AEP event in Figure 5.1.



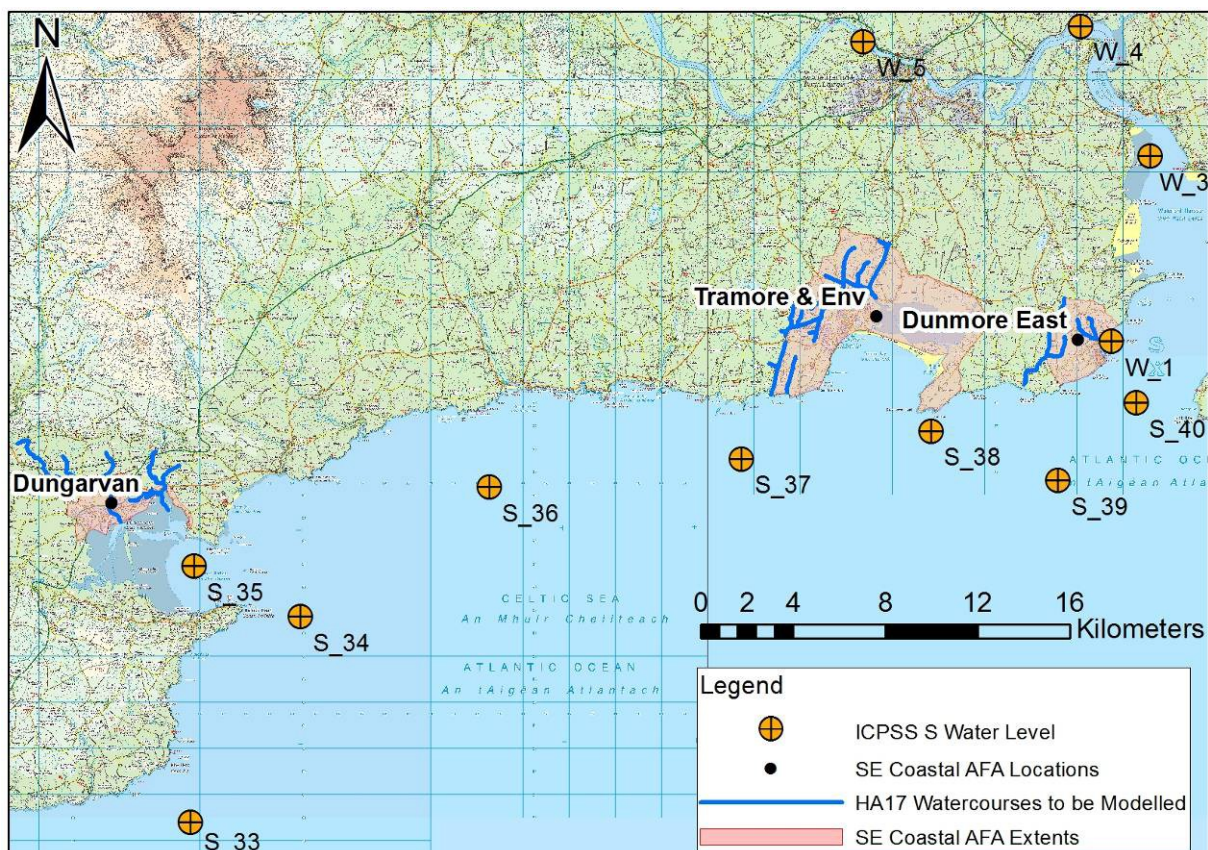
**Figure 5.1: 1% AEP Hydrographs for the small tributaries in Dunmore East AFA**

## 52 COASTAL HYDROLOGY

Analysis of the hydrological elements which contribute to coastal flood risk has been undertaken at a national level through the Irish Coastal Protection Strategy Study (ICPSS) and the Irish Coastal Wave and Water level Study (ICWWS). This study does not seek to re-analyse these elements of coastal flood risk but rather seeks to combine them, along with the fluvial elements where applicable, such that the total combined fluvial and coastal flood risk is assessed on an AFA by AFA basis.

### 5.2.1 ICPSS Levels

Outputs from the ICPSS include extreme tidal and storm surge water levels being made available around the Irish Coast for a range of AEPs. The location of ICPSS nodes are shown in Figure 5.2. In relation to Dunmore East there is one node in Dunmore Bay (W1) which is most appropriate. Tramore and Environs has two relevant ICPSS nodes, with one at either end of Tramore Bay (S37 & S38). In relation to Dungarvan, node S35 is located within Dungarvan Harbour and as such is the most relevant.



**Figure 5.2: Location of ICPSS Nodes in Relation to Coastal AFAs**

Levels for a range of AEPs have been extracted from the ICPSS and are shown in Table 5.1.

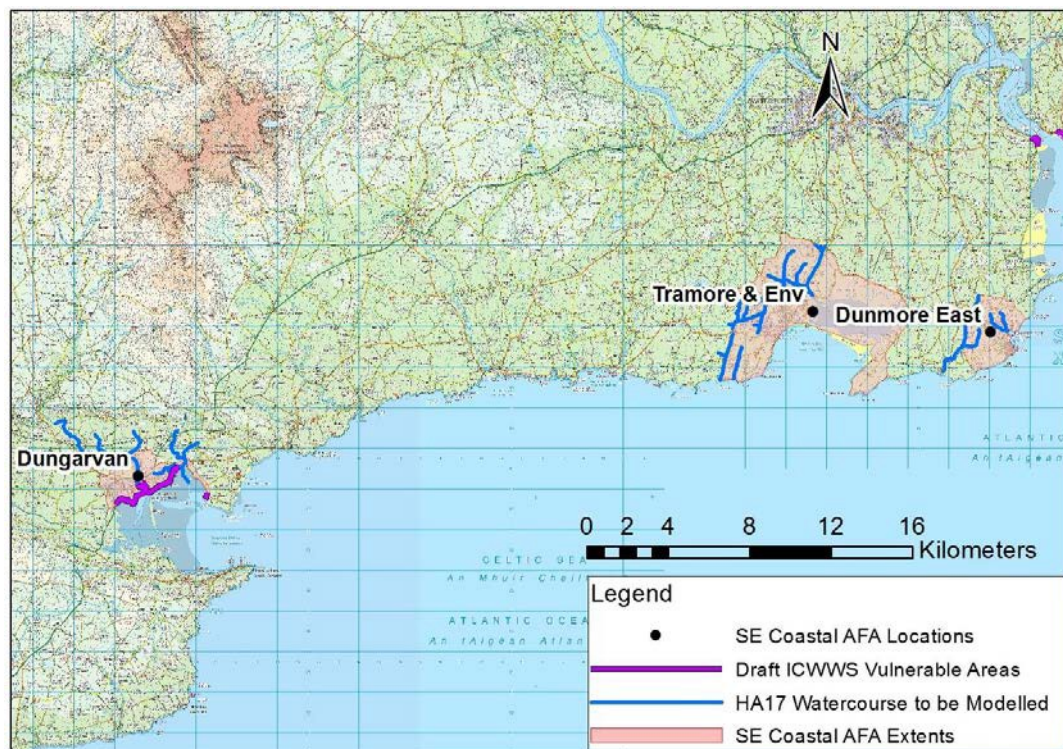
**Table 5.1: ICPSS Level in Close Proximity to HA17 AFAs**

ICPSS Node	AFA	Annual Exceedance Probability (AEP) %							
		2	5	10	20	50	100	200	1000
		Highest Tidal Water Level to OD Malin (m)							
S35	Dungarvan (incl Duckspool and Sallybrook)	2.19	2.28	2.35	2.41	2.50	2.56	2.62	2.77
S37	Tramore and Environs	2.12	2.20	2.27	2.33	2.41	2.47	2.53	2.67
S38		2.08	2.17	2.23	2.29	2.38	2.44	2.50	2.64
W1	Dunmore East	2.12	2.21	2.27	2.33	2.41	2.47	2.53	2.66

(Extracted from: Irish Coastal Protection Strategy Study Phases 2 & 3 – Technical Report ref: IBE0071/June2010 & IBE0104/June2010)

## 5.2.2 ICWWS Levels

The ICWWS was progressed by OPW in order to consider the potential risk associated with wave overtopping at exposed coastal locations. At the time of preparation of this report the study was ongoing but preliminary analysis was made available for the South Eastern CFRAM Study to identify the areas within HA17 which had been identified as potentially vulnerable to this flood mechanism. The length of vulnerable coastline and the affected AFAs are shown in Figure 5.3.



**Figure 5.3: Draft ICWWS potential areas of vulnerable coastline**

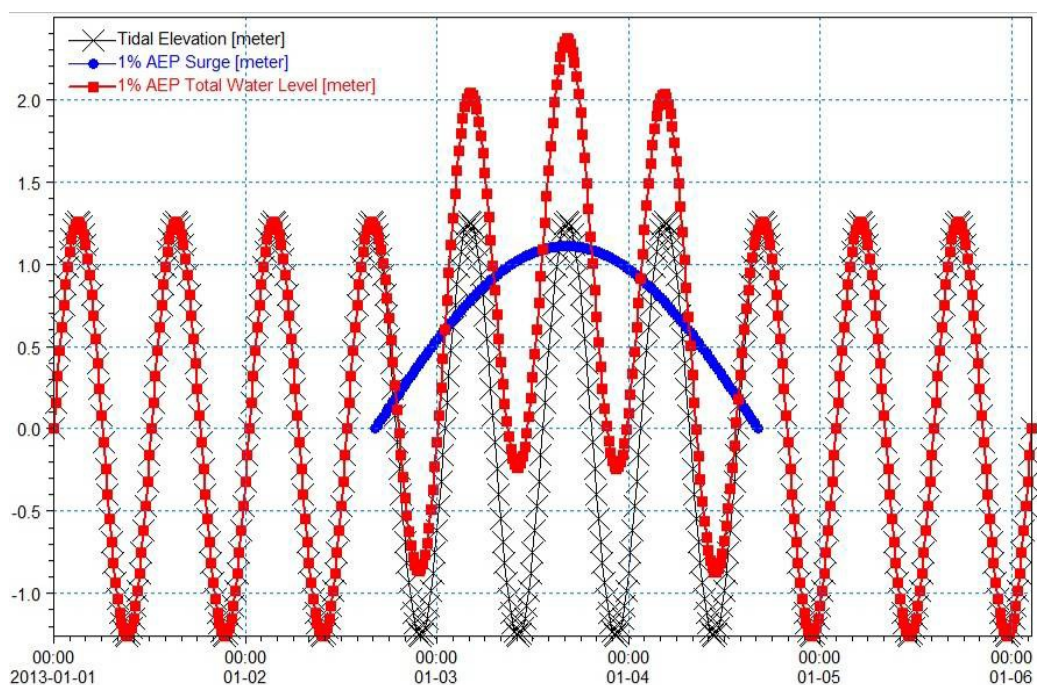


As shown in Figure 5.3 only the Dungarvan AFA has a coastline identified as potentially vulnerable to flooding due to wave overtopping. The ICWWS study will provide outputs in the form of a range of combinations of water level and wave characteristics (wave height, period, frequency and the joint probability assessed extreme water level) for each AEP (%).

### 5.2.3 Consideration of ICPSS and ICWWS Outputs

It is important to note that the outputs from both the ICPSS and the ICWWS are to be considered separately. Tidal boundaries will be applied within the 2D models at a scale and distance necessary to capture the complete effects of a dynamic tide and the propagation effects within Dungarvan Harbour, Tramore Bay and the Back Strand and also in Dunmore Bay.

At all AFAs (where fluvial flooding has been identified as a consideration within the model) the ICPSS levels will be applied for a range of joint probability scenarios (as detailed in Section 5.3.2) in order to determine the most onerous flood outline for any AEP. The levels which have been derived from the ICPSS will be applied within the 2D portion of the hydraulic (hydrodynamic) models. All ICPSS levels (Table 5.1) will be applied as the maximum level on the oscillating average tidal cycle observed at the tidal gauge at Wexford. A typical 1% AEP surge on tidal cycle to staff gauge zero is shown in Figure 5.4 below. Bathymetric and cross sectional survey has been undertaken within the tidal reaches of coastal models in order to accurately capture the effects of tidal propagation within the estuaries and into the tidal reaches of the watercourses where relevant. Full details on the application of the ICPSS levels at the coastal boundaries will be contained within the subsequent Hydraulic Modelling report.



**Figure 5.4: Typical 1% AEP Coastal Boundary Makeup (to Staff Gauge Zero)**

It is important to note that the outputs from the ICWWS are not directly applicable through the standard 2D hydraulic modelling packages used for coastal flood modelling. The assessment of the volume of flood water from wave overtopping is a function of the outputs from the ICWWS (wave height, period, frequency and the joint probability assessed extreme water level), the duration of the event and the dimensions and hydraulic performance of the sea defence and foreshore. At Dungarvan, identified as vulnerable to wave overtopping, preliminary analysis will identify the location and length of sea defence / frontage which is vulnerable to wave overtopping. This section will then be assessed against the range of wave / extreme water level combinations for each annual exceedance probability (AEP %) to determine the most onerous scenario. The total overtopping volume from the most onerous scenario for each AEP will then be assessed against the digital terrain model (LiDAR based) to ascertain the mapped flood extents, depth and hazard behind the sea defence / frontage within the AFA. Further details of the methodology for assessment and modelling of the wave overtopping flood risk will be contained within the Hydraulic modelling report.

### **5.3 JOINT PROBABILITY**

Joint probability is a minor consideration within HA17 in relation to the occurrence of fluvial – fluvial events (where extreme flood events on tributaries and the main channel of rivers coincide) as most of the fluvial model branches represent small catchments which are likely to have similar critical storm durations. Joint probability is a greater consideration within HA17 in relation to the downstream tidal reaches of the modelled watercourses where coastal – fluvial events could potentially combine to create a more onerous cumulative flood scenario such as within the Back Strand at Tramore and the tidal reaches of the Colligan and Glendine Rivers at Dungarvan.

#### **5.3.1 Fluvial – Fluvial**

There are few significant watercourse confluence points on the fluvial models within HA17 where consideration must be given to the probability of coincidence of flood flows within the model. The rivers to be modelled represent smaller catchments where the critical storm in the confluent sub-catchments is likely to be similar and the hydrological conditions which cause fluvial flood events have a low degree of variance across the model extents. In addition RPS has specified a high number of HEPs such that as we move down the model, i.e. past confluence points, the hydraulic modeller has to hand the design flows downstream of the confluence point such that they can check that the sum of the inflows within the tributary and the main channel are creating the correct frequency conditions downstream of the confluence point. Where these conditions are not being achieved the modeller will adjust the flows depending on the relationship between catchment descriptors of the main channel and tributary such that the joint probability relationship can be determined to create the correct frequency conditions downstream of the confluence point. This is a modelling consideration and may require an iterative approach. These adjustments will be carried out in line with the guidance provided in FSUWP 3.4 'Guidance for River Basin Modelling' and detailed in the Hydraulic Modelling report.

### 5.3.2 Fluvial – Coastal

In terms of HA17, this category of joint probability may be relevant to all the models as the downstream extents are all within tidally influenced reaches. The RPS methodology for assessing joint probability for coastal and fluvial flooding is outlined in the CFRAM Study technical note 'NTCG GN20 Joint Probability Guidance (RPS, June 2013)'. It advocates a stepped approach to the consideration of fluvial coastal joint probability whereby the relevance is assessed to ascertain at which sites dependence may exist and further analysis is needed:

*The first stage in any Joint Probability analysis should be to ascertain whether the flooding mechanisms in any particular area, either AFA or MPW, actually warrant the consideration of the joint probability of occurrence. This screening stage should involve a review of all existing information on flooding within the area of interest, such as records of historic events or previous studies including the output from the CFRAM PFRA and the complementary ICPSS data. Where this review identifies either a significant overlap in the areas of fluvial and tidal flood risk or a proven history of significant flooding from both sources, joint probability should be considered. Where the flooding mechanism is heavily dominated by one particular source it is questionable whether joint probability analysis is justified.*

An initial screening process has been undertaken on the three AFAs within HA17 all of which have been identified as potentially at risk from fluvial and coastal flooding. The results of this screening are shown in Table 5.2.

**Table 5.2: Initial Screening for Relevance of Joint Probability**

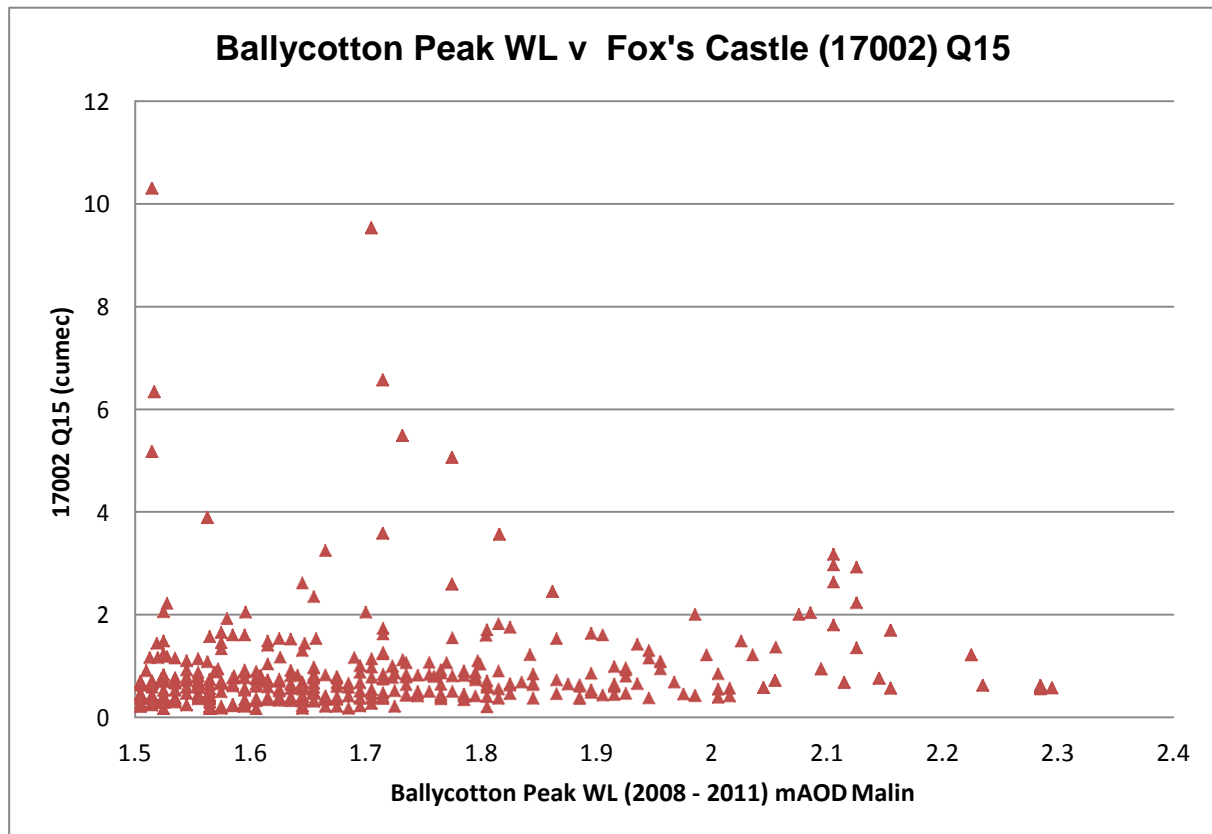
HA / Model No.	AFA Name	Evidence / History of Joint Occurrence	Comments	Further JP Analysis
Model 1	Dungarvan (inc. Duckspool & Sallybrook)	Yes	Evidence of joint occurrence and big overlap of coastal and fluvial flood extents on the Colligan and Glendine Rivers	Yes
Model 2, 3 & 4	Tramore & Environs	Yes	Likely to be significant in the low lying Back Strand area (downstream reaches of model 2) but other watercourses are relatively steep with no overlapping fluvial and coastal flood extents.	Yes (Model 2 only)
Model 5 & 6	Dunmore East	Yes	Watercourse reaches relatively steep within the AFA extents. Evidence seems to be in relation to pluvial and coastal	No



Following initial screening, models 3, 4, 5 & 6 can be removed from the consideration of joint probability of fluvial and coastal flood events. This is not to say there is no evidence of a tidal influence at these locations but rather that there is no known evidence of joint fluvial and coastal flood occurrence and that there are no low lying areas on the lower reaches that would be particularly sensitive to such a joint occurrence, over and above a fluvially or tidally dominant event in isolation. For each of these models suitable conservative tidal downstream boundary conditions will be applied such as the highest astronomical tide, oscillating such that there is coincidence between peak tide and hydrograph. It is not thought this will lead to unrealistic downstream flood extents as the overlap of the most extreme 0.1% AEP events, when considering the PFRA and ICPSS outlines, is minimal. Nevertheless this will be reviewed following initial model runs to check that this assumption is valid.

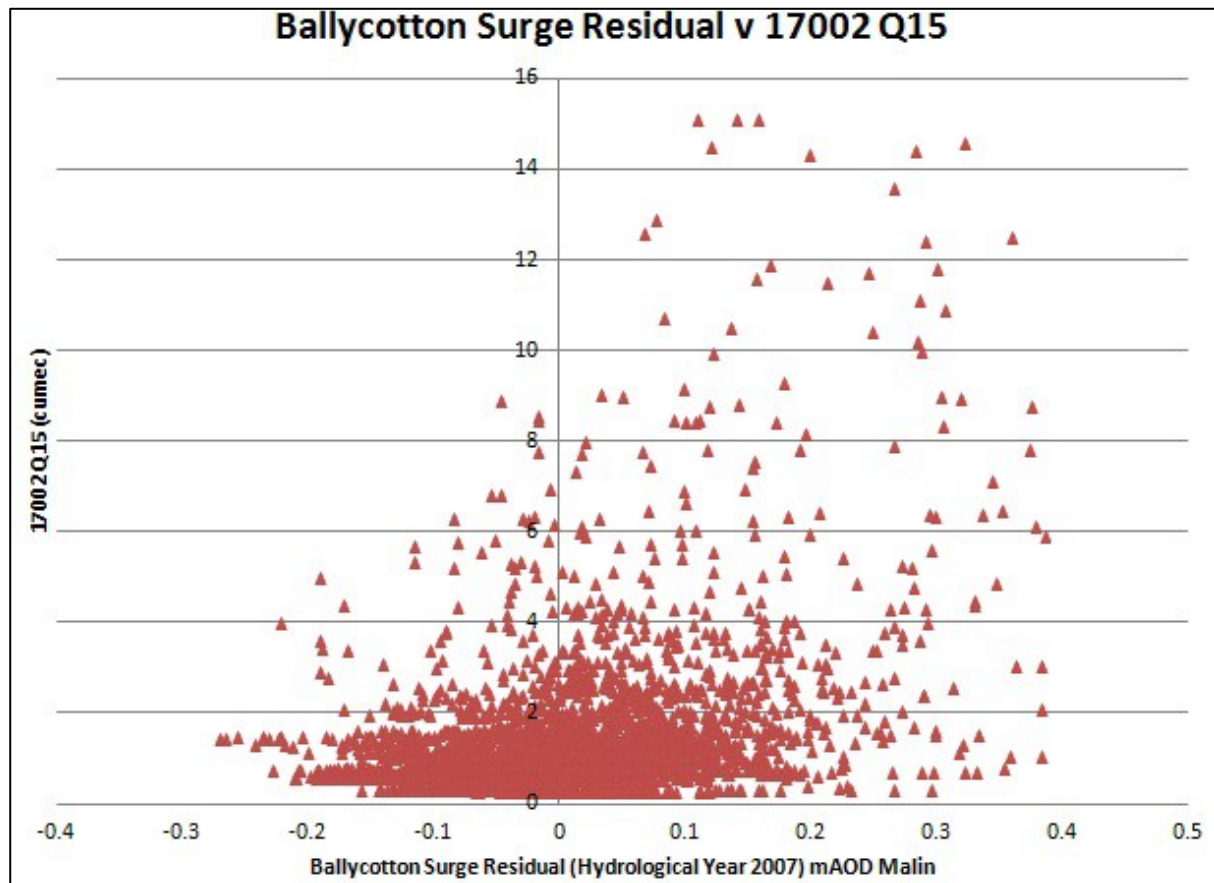
The modelling of Dungarvan and the Back Strand area of Tramore must consider the occurrence of joint probability further. The result of a joint occurrence of both fluvial and coastal flood conditions would have a significant impact on the harbour / estuary areas of both AFAs. There is both documentary evidence of the joint occurrence of rainfall driven (possibly fluvial) and coastal flooding within both AFAs. Also flood outlines for both types of events overlap significantly, suggesting the consequences of joint occurrence would lead to a significantly more onerous flood scenario.

The next stage in assessing the joint probability is to review the available data to ascertain if there is a dependence relationship between extreme coastal and fluvial events. There is limited coastal water level data available in close proximity to either Dungarvan or Tramore. The nearest long term gauge record available for comparison is at Cobh approximately 60km to the south west of Dungarvan. This record may be affected by localised tidal propagation effects within Cork Harbour and as such may not be representative of the more exposed coastal location of the HA17 AFAs. There is however one short term tidal gauge record at Ballycotton approximately 40km to the south west of Dungarvan and 70km south west of Tramore. Continuous data is available for the years 2008, 2010 and 2011. In terms of fluvial hydrometric gauge records there are no gauging stations located on any of the modelled watercourses within HA17 however data is available on the Tay River between Dungarvan and Tramore at Fox's Castle (17002 – EPA). This is a relatively small coastal catchment and it is therefore considered appropriate to ascertain if there is any correlation between coastal and fluvial data within HA17. Peak high water levels were extracted from the Ballycotton tidal gauge data and compared against the simultaneous flow record at the Fox's Castle gauge. As shown in Figure 5.5 very little positive correlation is evident.



**Figure 5.5: Peak Water Level at Ballycotton versus Flow at Fox's Castle G.S.**

Despite there being no real positive correlation evident it is not necessarily the case that the factors which affect fluvial and coastal flooding in HA17 are totally independent. As well as the total water level data available at Ballycotton there is also one year (hydrological year 2007) of storm surge residual data. This data represents the water level data with the effect of the tide removed such that only the storm surge driven rise in water levels is present. This data was plotted against the simultaneous flow data with results shown in Figure 5.6. It can be seen that, with the effect of the tide removed, there is now a much clearer positive correlation. This would be expected as the climatic conditions which typically lead to storm surge on the south coast, weather systems emanating from the prevailing south westerly direction, are the same as those which generate the majority of precipitation in the HA17 catchments.



**Figure 5.6: Surge Residual at Ballycotton versus Flow at Fox's Castle G.S.**

Analysis of both sets of data shows that there is dependence between the factors which affect fluvial flooding and the factors which affect coastal flooding in HA17. However in relation to coastal flooding the effect of surge appears to be dwarfed by the oscillation of the tides which are driven by astronomical factors and can be considered totally independent from meteorological factors. When we consider total peak water levels the correlation is so diluted as to be barely evident. It is this total water level dataset which is most relevant in terms of the joint probability relationship as this represents the real world scenario. As correlation between total water levels and fluvial flood flow within HA17 can be considered to be negligible, it is proposed to follow a simplified conservative approach whereby the 50% AEP design event is maintained for one mechanism while the whole range of design AEP events for the other mechanism are tested and vice versa. This may be subject to sensitivity testing where necessary to ensure the approach does not yield results which could lead to unrealistic flood extents or over design of measures.

## 6 FUTURE ENVIRONMENTAL AND CATCHMENT CHANGES

There are a number of future potential changes which may affect the outputs of this study and as such it is prudent that they are identified and their potential impact quantified so that the outputs can accommodate these changes as much as practically possible. This chapter outlines potential environmental changes such as climate change and changes to the catchment such as afforestation and changing land uses. HA17 is a predominantly rural catchment with much of the land given over to pasture. The largest urban area is Tramore town located on the shores of Tramore Bay and Back Strand. Urbanisation along with potential management and policy changes are considered in this chapter. The design flow estimations for Mid Range and High End Future Scenarios (MRFS and HEFS) that have been calculated based on the findings of this chapter are included in Appendix B for each HEP.

### 6.1 CLIMATE CHANGE

According to the United Nations Intergovernmental Panel on Climate Change (2007) there is “unequivocal” evidence of climate change and furthermore:

*"most of the observed increase in global average temperatures since the mid-20th century is very likely due to the observed increase in anthropogenic greenhouse gas concentrations."*

(Climate Change 2007, IPCC, Fourth Assessment Report AR4)

Further to this carbon dioxide levels in the atmosphere were observed at over 400 parts per million in Hawaii. This is considered a milestone threshold and is at a level last thought to have occurred several million years ago when the Arctic was ice free and sea levels were up to 40m higher<sup>1</sup>.

The effects of climate change on flood risk management are obvious but in terms of fluvial flooding they are not straightforward to quantify. Changes in sea level have direct impact on coastal flooding and a range of predictions on projected rise are available. A number of meteorological projections are also available for changes in rainfall but these have a wide degree of variance particularly from season to season and are difficult to translate into river flow. A recently completed study by the National University of Ireland, Maynooth (Murphy et al, 2011) provides an indication of the uncertainties associated with standard allowances made for precipitation and river flow in future climates. This is discussed further in Chapter 7.

#### 6.1.1 HA17 Context

Research into climate change in Ireland is coordinated by Met Éireann through the Community Climate Change Consortium for Ireland ([www.c4i.ie](http://www.c4i.ie)). Research summarised in the report 'Ireland in a

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<sup>1</sup> <http://www.theguardian.com/environment/2013/may/10/carbon-dioxide-highest-level-greenhouse-gas>

Warmer World – Scientific Predictions of the Irish Climate in the 21<sup>st</sup> Century’ (Mc Grath *et al*, 2008) seeks to quantify the impact of climate change on Irish hydrology and considers the impacts on nine Irish catchments all of which were outside HA17 but include the Suir (HA16) and the Barrow (HA14). The ensemble scenario modelling from the regional climate change model predicts that between the two periods of 1961 – 2000 and 2021 – 2060 that Ireland is likely to experience more precipitation in autumn and winter (5 – 10%) and less precipitation in summer (5 – 10%). Between the periods of 1961 – 2000 and 2060 – 2099 this trend is likely to continue with increases of 15 – 20% generally, but up to 25% in the northern half of the country in autumn and drier summers of up to 10 – 18%.

The report seeks to further quantify the impact on hydrology in Ireland through the use of a HBV-Light conceptual rainfall run-off model (provided by Prof. Jan Seibert of Stockholm University) to simulate the effects of climate change on stream flow within the nine Irish catchments. The HBV-Light conceptual rainfall run-off model of the Suir catchment (HA16) was calibrated using historical meteorological data against the hydrometric gauge record at the Clonmel gauging station (16011). Validation of the model found that the Suir model was well calibrated when it came to simulating the seasonal cycle of mean monthly and mean winter flow with slight over-estimation but simulated annual maximum daily mean flow was overestimated. Risk outputs from the model can be considered to be over-estimated. The HBV-Light conceptual rainfall run-off model of the Barrow catchment (HA14), was calibrated using historical meteorological data against the hydrometric gauge record at the Royal Oak gauging station (14018). Validation of the model found that the Barrow model was not quite as well calibrated when it came to simulating the mean winter and summer flows. The flows were overestimated when compared against the observed historic data from the gauging station at Royal Oak and as such the risk outputs from the model can be considered to be overestimated. Following simulation of the meteorological climate change ensembles within the run-off models the following observations were made in both catchments for the changes between the periods (1961 – 2000) and (2021 – 2060):

- Reductions in mean daily summer flow of up to 60% and increases in mean winter flow of up to 20% within both catchments;
- The risk of extremely high winter flows is expected to almost double in the Suir. Mixed results were obtained for the Barrow where the flows associated with certain return periods in the past will have a greater return period in the future, which is explained by the effect of damped and even hydrographs resulting in a longer time scale to respond to changes in precipitation than faster responding catchments;
- No definite increase in annual maximum daily mean flow is expected in either the Suir or Barrow catchment.

In addition to the research undertaken by C4i the paper titled ‘Quantifying the cascade of uncertainty in climate change impacts for the water sector’ (Dept. of Geography, National University of Ireland, Maynooth, 2011) seeks to quantify the cumulative effect of uncertainties on catchment scale climate change run-off models from uncertainties in emissions scenarios, climate model selection, catchment

model structure and parameters. This paper concludes that uncertainties are greatest for low exceedance probability scenarios and that there is considerable residual risk associated with allowances of +20% on fluvial flows for climate change, as recommended in 'Assessment of Potential Future Scenarios for Flood Risk Management' (OPW, 2009) for the MRFS. In light of this conclusion there is an even greater weight to be placed on higher end future predictions for climate change. The use of the OPW HEFS for fluvial flows of +30% is even more relevant in this context.

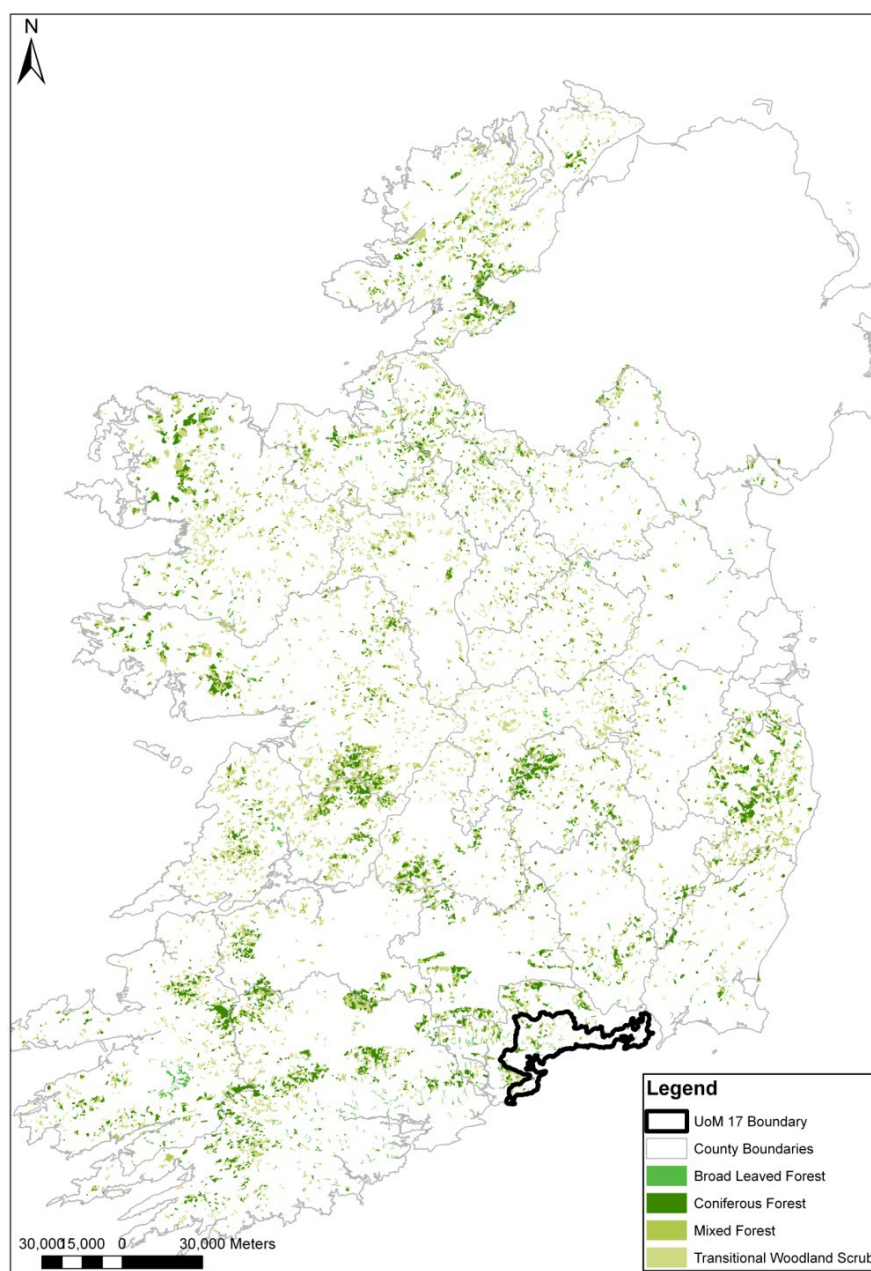
### **6.1.2 Sea Level Rise**

Research from c4i summarised in the aforementioned report states that sea levels around Ireland have been rising at an annual rate of 3.5mm per year for the period 1993 – 2003 which is higher than the longer term rate of 1.8mm per year for the period 1963 – 2003. This trend is likely to be reflected in the Southern Region with a 'net trend' (allowing for isostatic adjustment of the earth's crust) of 3.1-3.5mm per year; and more modest in the Irish Sea with a 'net trend' of 2.3 – 2.7mm per year. On top of this the report notes that storm surges are likely to increase in frequency.

## 62 AFFORESTATION

### 6.2.1 Afforestation in HA17

There is much legislation governing forestry practices in Ireland but it is implemented through the document 'Growing for the Future – A Strategic Plan for the Development of the Forestry Sector in Ireland' (Department for Agriculture, Food & Forestry, 1996). The plan points out that over the period from 1986 to 1996 afforestation saw quite a dramatic growth in Ireland from a level of approximately 70 km<sup>2</sup> annually to almost 240 km<sup>2</sup> annually in 1996 largely driven by a growth in private forestry activities. Within HA17 the current forest coverage as recorded in the 2006 CORINE land maps for the hydrometric area / UoM is shown in a national context by Figure 6.1.



**Figure 6.1: CORINE 2006 Forest Coverage in HA17 Compared to the rest of Ireland**

The total forested area, including transitional woodland scrub, within HA17 is 61.3km<sup>2</sup> which is approximately 9.5% of the total area. The average for the country is approximately 10%. The densest coverage is in the west in the southern foothills of the Monavullagh Mountains. Comparison of the CORINE 2006 database to the 2000 database indicates that there has been some increase in the forested area as shown by the pink and blue areas in Figure 6.2.

As can be seen from Figure 6.2 additional pockets of forested area appeared between 2000 and 2006 (areas of pink and blue) but this has mostly been in transitional woodland scrub (pink areas) as opposed to actual forest. Furthermore, there are areas where a decrease has occurred. The net effect has been an overall decrease in forested area within HA17 as shown by the breakdown in Table 6.1.

**Table 6.1: Afforestation from 2000 to 2006**

	CORINE 2000		CORINE 2006		Change		Annualised Change	
	Area (km <sup>2</sup> )	% of catch.	Area (km <sup>2</sup> )	% of catch.	Area (km <sup>2</sup> )	% of catch.	Area (km <sup>2</sup> )	% of catch.
<b>Forest</b>	32.6	<b>5.1</b>	30.5	<b>4.75</b>	-2.1	<b>-0.35</b>	-0.35	<b>-0.06</b>
<b>Transitional Woodland Scrub</b>	35.1	<b>5.5</b>	30.8	<b>4.79</b>	-4.3	<b>-0.71</b>	-0.72	<b>-0.12</b>
<b>Total</b>	67.7	10.6	61.3	9.54	-6.4	<b>-1.06</b>	-1.07	<b>-0.18</b>
<b>Total Countrywide</b>	6,631	<b>9.4</b>	7,087	<b>10.1</b>	456	<b>+ 0.65</b>	76	<b>+0.11</b>

From Table 6.1 it can be seen that total forest / woodland scrub has decreased in HA17 between 2000 and 2006 where the area of both actual forest coverage and transitional woodland scrub has dropped slightly. When considered together the total area of forest / woodland scrub as a proportion of the catchment (9.54%) is slightly lower than the national average of approximately 10%. HA17 has experienced a 0.18% annual decrease in total forestry land cover compared to a national average increase of 0.11% per year. If the annualised decrease in afforestation were to continue for the next 100 years forest coverage in HA17 would be non-existent.



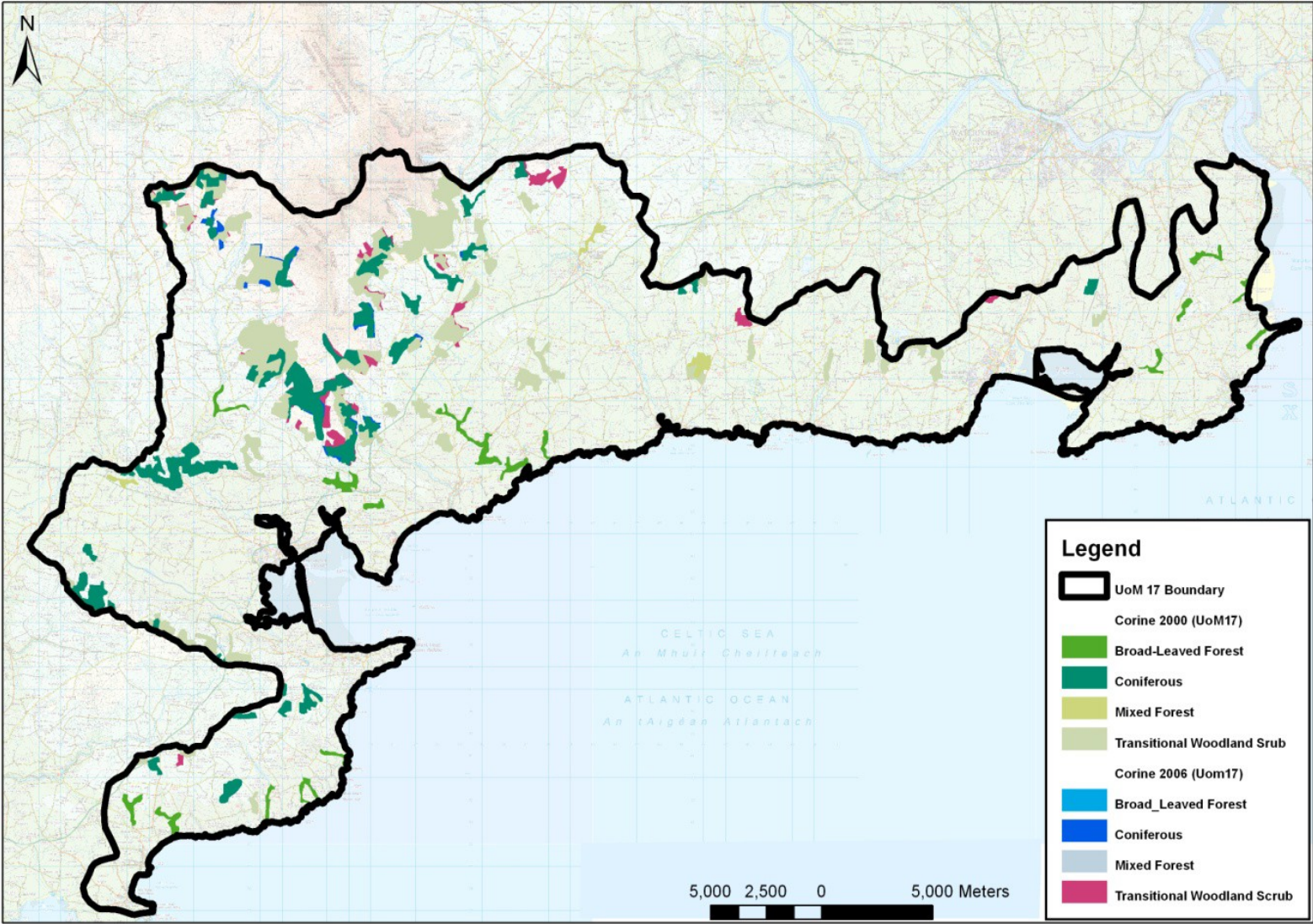
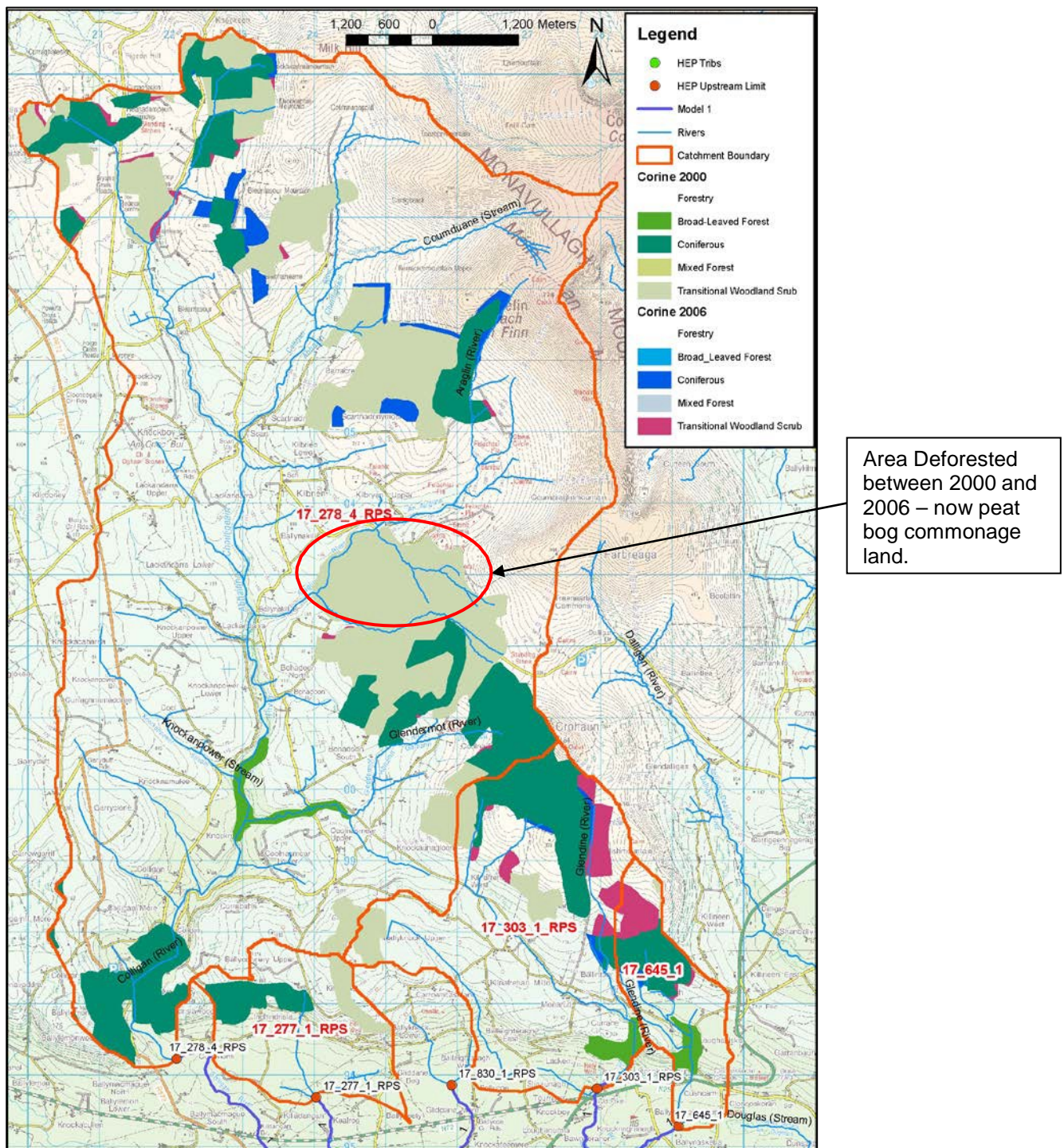


Figure 6.2: Forest Coverage Changes in HA17



Figure 6.2 indicates that the densest coverage of forestry within HA17 is to the west. More specifically, the catchments of Model 1 merit closer consideration. Figure 6.3 provides a closer look at the catchments containing forestry within Model 1.



**Figure 6.3: Forest Coverage Changes – Model 1**

As indicated by Figure 6.3, the following HEP catchments contain forested areas:

- 17\_284\_4\_RPS
- 17\_303\_1\_RPS

- 17\_645\_1\_RPS
- 17\_277\_1\_RPS

It is also clear that the smaller catchments 17\_303\_1\_RPS and 17\_645\_1\_RPS have a high proportion of forest coverage compared to total area. Overall there are pockets of increased forestry area across the upstream catchments of Model 1, both coniferous and transitional woodland scrub. Table 6.2 indicates the percentage coverage of forestry per relevant sub catchment in Model 1.

**Table 6.2: Changes in Forestry Coverage between 2000 and 2006 – Model 1 Catchments**

HEP Catchment	Catchment Area (km <sup>2</sup> )	FOREST 2000 (% of catchment)	FOREST 2006 (% of catchment)	% change	Annualised Change %
17_284_4_RPS	80.9	21	17	-4	-0.7
17_277_1_RPS	4.5	20	20	0	0
17_645_1_RPS	3.2	28	38.5	+10.5	+1.7
17_303_1_RPS	11.6	24	29	+5	+0.8
Total Countrywide					+0.11

Table 6.2 indicates that there has been a reduction in forestry coverage in the largest catchment 17\_284\_4\_RPS which contains the upper reaches of the Colligan River and its tributaries. The main area of deforestation is annotated on Figure 6.3. This area is peat bog and recent aerial imagery indicates that it has remained deforested, and is now used as commonage land (<http://www.npws.ie/mapsanddata/habitatspeciesdata/>).

Catchment 17\_277\_1\_RPS experienced no change in forestry coverage. The remaining two catchments experienced an increase in forestry coverage as indicated in Table 6.2. These two catchments 17\_645\_1\_RPS and 17\_303\_1\_RPS have relatively high forestry coverage and experienced a significant annualised increase between 2000 and 2006 in relation to the national average of +0.11. In particular the Glendine River catchment (17\_645\_1\_RPS) increased by an annual rate of 1.7% and had almost 40% coverage in 2006.

### 6.2.2 Impact on Hydrology

A number of studies have been carried out on a range of catchments in an attempt to capture the effects of afforestation on run-off rates and water yields. The DEFRA (UK) report 'Review of impacts of rural land use management on flood generation' (2004) considers a number of case studies where the effects of afforestation on the catchment run-off were considered. The report concluded that the effects of afforestation are complex and change over time. A summary of the main findings in relation to afforestation are given below in relation to the River Irthing catchment in the north of England:

- Water yield tends to be less from forest than pasture;

- In the Coalburn sub-catchment (1.5 km<sup>2</sup>) study peak flows were found to increase by 20% in the first 5 years and times to peak decreased, with the effect reducing over time (to 5% after 20 years). The time to peak was also reduced;
- In the overall River Irthing catchment (335 km<sup>2</sup>) the same effect was observed but to a much smaller degree.

The effects which were observed are considered to be largely due to the associated land drainage works that accompany afforestation for the purposes of harvesting. However in the case of HA17 there has not been found to be any increase in commercial forestry coverage with a reduction in forestry coverage in the Colligan catchment. In addition, transitional woodland scrub is most likely due to natural growth and is highly unlikely to be accompanied by the type of drainage works associated with industrial forestry practices. Although some upland catchments in HA17 are already forested it seems that the likelihood of future growth of commercial forestry in HA17 is low. The overall impact of afforestation is likely to be negligible in the greater catchment considering the small proportion, and small likely increase if any in proportion of forest coverage in the catchment. Commercial afforestation with the aforementioned drainage works are unlikely to significantly affect the future catchment and therefore its future hydrological regime.

However the models receiving waters from upland areas may be susceptible to the potential impacts of afforestation and as such some sensitivity analysis of the effects of afforestation would be prudent. It is recommended that sensitivity analysis to quantify the effects of potential afforestation is analysed at:

- Model 1 – Dungarvan (in particular the Colligan and Glendine Rivers)

This will be modelled for the HEFS by increasing the peak design flows by 10% to reflect the recommended increase to Standard Percentage Runoff in Table 6.3 below. This table also recommends reducing the Time to Peak of design hydrographs to reflect the increased flashiness of a catchment due to afforestation. However upon detailed consideration of this allowance it was decided that it was ineffective at a catchment scale. Reducing the time to peak of a design hydrograph representing flood conditions of a tributary is likely to reduce overall flow in the model (and crucially the receiving AFA downstream) by causing the design peak to occur before the peak flow in the main channel. In other words, the effect of combining peak flows to represent the worst case scenario in terms of flood flows reaching the AFA could actually be reduced by reducing the time to peak of tributaries. Therefore it was not considered effective in determining the susceptibility of the AFA to future flow conditions

**Table 6.3: Allowances for Effects of Forestation / Afforestation (100 year time horizon)**

Mid Range Future Scenario (MRFS)	High End Future Scenario (HEFS)
- 1/6 Tp <sup>1</sup>	- 1/3 Tp <sup>1</sup> + 10% SPR <sup>2</sup>

*Note 1: Reduce the time to peak (Tp) by one sixth / one third: This allows for potential accelerated run-off that may arise as a result of drainage of afforested land*

*Note 2: Add 10% to the Standard Percentage Run-off (SPR) rate: This allows for increased run-off rates that may arise following felling of forestry*

(Extracted from 'Assessment of Potential Future Scenarios for Flood Risk Management' OPW, 2009)

### 6.3 LAND USE AND URBANISATION

The proportion of people living in urban areas (classified as towns with a population of 1,500 or more) has increased dramatically in recent years with a nationwide increase of over 10% in the total urban population recorded between the 2006 census and the 2011 census. The total population within County Waterford (containing all of HA17) has increased by varying degrees since 1991 as demonstrated by Table 6.4.

**Table 6.4: Population Growth in the Counties of HA17 (Source: Central Statistics Office of Ireland, CSO)**

		1991	1996	2002	2006	2011
<b>County Waterford</b>	Population (Number)	51,296	52,140	56,952	62,167	66,960
	Actual Change Since Previous Census (Number)	-326	844	4,812	5,215	4,793
	<b>Population Change Since Previous Census (%)</b>	<b>-0.6</b>	<b>1.6</b>	<b>9.2</b>	<b>9.2</b>	<b>7.7</b>

As indicated by Table 6.4 County Waterford has seen quite significant population rise since 1991 particularly within the last three record periods. The county has experienced a 1.4% average annual population growth rate since 1991 with an average of 1.7% annual growth rate since 1996.

There has been no corresponding increase in the share of the rural population since 2006 and as such the data would suggest that the population growth within HA17 has been almost entirely within the urban centres.

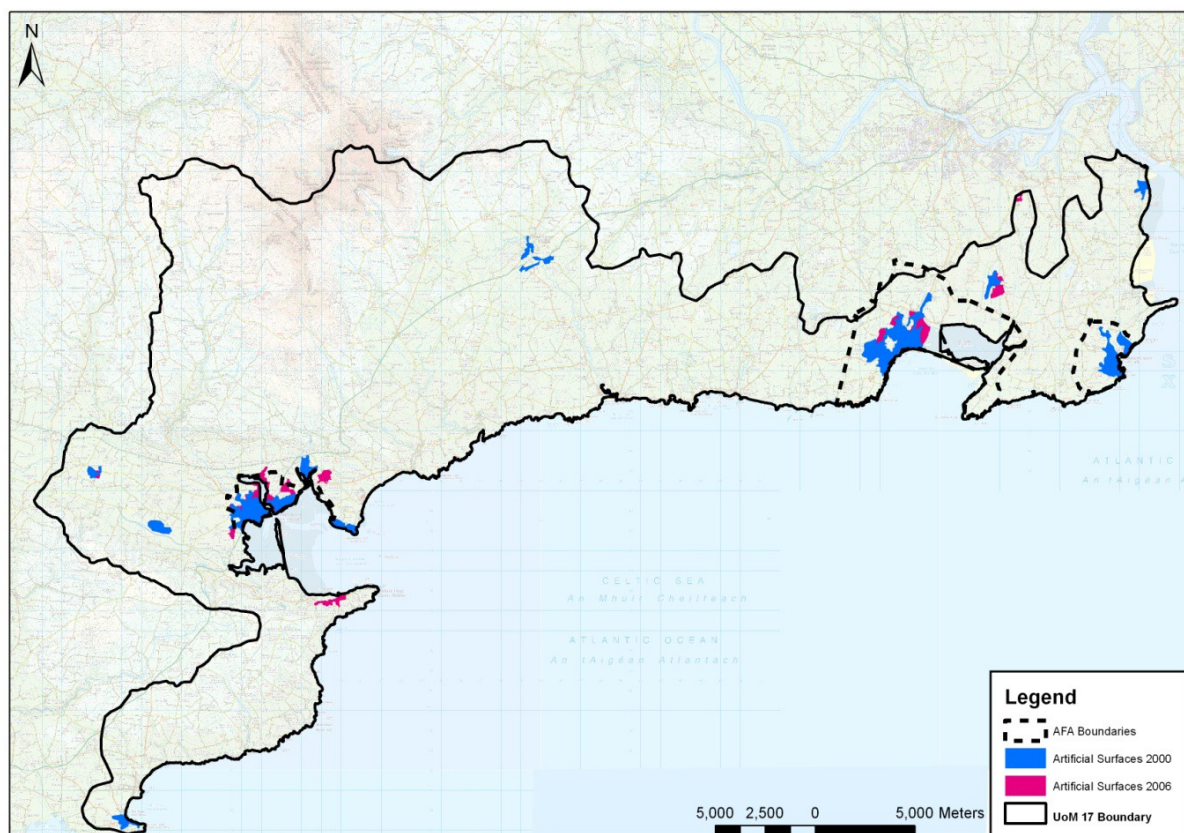


Table 6.5 below confirms that urban population growth within the urban AFAs (population > 1500) for the period 2006 – 2011 has been moderate ranging from 0.8% in Dunmore East up to 12.7% in Dungarvan over the five year census period.

**Table 6.5: Population Growth within Urban AFAs (Source: CSO)**

Urban Area	County	Population 2011	Increase Since 2006 (%)
Dungarvan	Waterford	9,427	12.7
Dunmore east	Waterford	1,559	0.8
Tramore	Waterford	10,328	7.2

The total percentage population growth in these AFAs however is 6.9% for the period 2006 – 2011 which equates to an average annual growth rate of approximately 1.4%. To determine if these changes translate into equivalent increases in urbanised areas we must examine the CORINE database within HA17 and the changes from 2000 to 2006. A simple comparison of the datasets within the HA17 appears to show that there has been a notable increase in artificial surfaces within HA17 from 12.5 km<sup>2</sup> in 2000 to 15.4 km<sup>2</sup> in 2006 which represents an increase of just over 23% in six years (see Figure 6.4).



**Figure 6.4: HA17 CORINE Artificial Surfaces (2000 /2006)**

Closer inspection of the CORINE datasets shows that a notable proportion of this growth in artificial surfaces is due to changes outside the AFAs. There is an additional 0.8km<sup>2</sup> of discontinuous urban fabric and a 0.4km<sup>2</sup> extension of Waterford Airport outside the AFAs which account for 27% and 14% of the additional hardstanding in HA17 respectively. However it is assumed that Sustainable Urban Drainage Systems have maintained as close as possible to Greenfield run-off rates and therefore do not directly affect AFAs. For a more representative picture of the increase in urbanisation, the areas of hardstanding within the AFA extents were compared. The AFAs with an increase in the extent of artificial surfaces are:

- Dungarvan 31.3% increase (4.6% annually)
- Tramore and environs 21.7% increase (3.3% annually)
- Dunmore 3.4% increase (0.6% annually)

The annual growth rate in the artificial surfaces within all HA17 AFA extents is 2.8%.

The CSO has also produced Regional Population Predictions for the period of 2011 - 2026 based on a number of scenarios considering birth rates and emigration. Under all the modelled scenarios the South East region is set to experience strong population growth.

Under the M0F1 Traditional model, which tends to reflect longer term growth trends, the projected population rise for the region in the 15 year period equals 8.6% equating to an average annual growth rate of 0.6%. Under the M2F1 Recent model, which tends to reflect more recent growth rates, the projected rise in population is 27% equating to an annual average growth rate of 1.8%.

Any estimation of the rate of urbanisation should consider the three measures of recent growth which have been examined along with the projected population increases from the CSO for the region. These are summarised in Table 6.6.

**Table 6.6: Historic Urbanisation Growth Indicators**

	Population in HA17 AFA Counties 1991 - 2011	Population in HA17 Urban AFAs 2006 - 2011	Artificial Surfaces (CORINE) within HA17 AFA Extent 2000 - 2006	CSO M0F1 Population Projection 2011 - 2016	CSO M2F1 Population Projection 2011 - 2016
Average Annual Growth Rate (%)	<b>1.4%</b>	<b>1.4%</b>	<b>2.8%</b>	<b>0.6%</b>	<b>1.8%</b>

Table 6.6 indicates that, based on the data and projections available that future urbanisation growth rates in HA17 are likely to be around 1% per annum. At the high end of projections a rate of approximately 2.5% appears realistic for HA17. Continuation of these growth rates for 100 years, the

period to be considered for the CFRAM Study future scenario, would lead to the Dungarvan catchment area (Model 1, Colligan River) becoming 9% and 37% urbanised respectively.

### 6.3.1 Impact of Urbanisation on Hydrology

The effect of urbanisation on run-off is well documented. The transformation from natural surfaces to artificial surfaces, which in almost all cases are less permeable, increases surface run-off such that it is generally faster and more intense. If we consider the FSU 'URBEXT' catchment descriptor at the most downstream FSU node in the Dungarvan catchment, currently 3.16, and represents the percentage of urbanisation within the catchment, the URBEXT could potentially rise to between 9% urbanised (based on growth of 1% per annum) and 37% urbanised (based on growth of 2.5% per annum) over a 100 year projection.

Using the FSU equation (WP 2.3) for index flow estimation ( $Q_{med}$ ) based on catchment descriptors the Urban Adjustment Factor (UAF) for the Dungarvan catchment at the most downstream FSU node would vary as shown in Table 6.7 for the 100 year high end (HEFS) and mid range (MRFS) future scenarios.

**Table 6.7: Potential Effect of Urbanisation on  $Q_{med}$  Flow in Dungarvan (Model 1)**

	Growth Rate (per annum)	URBEXT <sup>2</sup>	UAFS <sup>1</sup>	Total Catchment $Q_{med}$ Flow m <sup>3</sup> /s
Present Day	n.a.	3.16	<b>1.05</b>	33.1
100 Year MRFS	1.0%	8.55	<b>1.13</b>	37.4
100 Year HEFS	2.5%	37.33	<b>1.6</b>	53.0

Note 1: Urban Adjustment Factor  $(UAF) = (1 + URBEXT/100)^{1.482}$

Note 2: URBEXT is the percentage of urbanisation in the catchment

Note 3: Total Catchment – taken as most downstream FSU Node in HA12

Table 6.7 represents the overall Dungarvan catchment and as such can be considered a more generalised example of the potential effect of urbanisation. At one end of the scale, there are catchments with no existing urbanisation that could remain totally rural. This is likely to be the case in Models 3 and 4 (Tramore Environs) where URBEXT is currently zero. At the other end of the scale, there may be catchments representing small watercourses on the edges of AFAs which are currently totally rural but which could become totally urbanised in 100 years if the spatial growth of the urban fabric of the AFA occurs in the direction of that small catchment. In this scenario the application of growth rates to an existing URBEXT value of zero will have no effect and as such the effect could be missed using a methodology that applies growth factors to the URBEXT values. It must also be considered that any attempts to predict the spatial growth of AFAs on a 100 year time frame would be



highly uncertain as growth rates and growth direction are dictated by complex social, economic and cultural factors which cannot be predicted far into the future.

We must also consider the effect of recent developments in sustainable drainage policy and guidance. The move away from conventional drainage systems is likely to gather pace with the aim of these newer policies and systems to provide drainage for urban areas which recreates the run-off behaviour of the rural catchment in an attempt to mitigate flood risk. Sustainable drainage policy is already being implemented in Dublin through the Greater Dublin Strategic Drainage Strategy (GDSDS). It is largely in its infancy outside the capital but it would be expected to develop greatly throughout the time span of the future scenarios. Therefore the current effect of urbanisation on catchment run-off could be expected to reduce over time as sustainable drainage policy and systems develop.

Since HA17 has a relatively small number of Models containing a relatively small number of HEPs, the growth rates are considered on a model by model basis by applying a factor based on the current URBEXT values and the growth rates considered above of 1% and 2.5% respectively for the medium and high end future scenarios.

Small urban watercourses with catchments that emanate around the periphery of AFA extents are considered to become much more urbanised and as such will be considered as having URBEXTs of 50% for the mid range and 85% for the high end future scenarios (85% is considered the urban saturation level as some green spaces will always remain).

Based on these considerations the following future scenarios will be considered for the effects of urbanisation within HA10:

**Mid Range Future Scenario:**

- Urbanisation within catchment to increase by 1% per annum over 100 year projection (URBEXT multiplied by 2.7 up to a maximum of 85%)
- HEPs with present day URBEXT of 0 are given a future URBEXT of 2.7%
- Areas of sub-catchment or tributary catchment within the AFA which are susceptible to rapid urbanisation but which at present are predominantly undeveloped may be assumed to become half developed (URBEXT = 50%).

**High End Future Scenario:**

- Urbanisation within catchment to increase by 2.5% per annum over 100 year projection (URBEXT multiplied by 11.8 up to a maximum of 85%)
- HEPs with present day URBEXT of 0 are given a future URBEXT of 2.7%
- Areas of sub-catchment or tributary catchment within the AFA which are susceptible to rapid urbanisation but which at present are predominantly undeveloped may be assumed to become half developed (URBEXT = 85%).

The allowances for urbanisation are based on a robust analysis of population growth, recent increases in artificial surfaces and population projections from the CSO. However this is based on extrapolation of current growth rates which are dependent on complex social, economic and environmental factors. Furthermore the estimation of the UAF under FSU is based on data from existing urban catchments and therefore does not reflect the impact of recent policy changes and changes to drainage design guidelines where the emphasis is on developments replicating the existing 'greenfield' flow regime through attenuation and sustainable urban drainage systems. An approach has been developed that considers an adjustment factor for the HEPs across HA17. At the downstream end of models these adjustment factors will translate into increases in flow of approximately 8% and 40% for the mid range and high end future scenarios respectively. Small catchments which would be susceptible to full urbanisation are to be considered separately and will see their flows increase by up to 41% and 74% for the mid range and high end future scenarios respectively. That said, 49% of HEPs in HA17 are totally rural (present day URBEXT = 0) and are likely to remain so into the future. This includes Model 3 and Model 4.

There is high uncertainty in all of these allowances as discussed above and it is recommended that they are reviewed at each cycle of the CFRAM Studies.

## **6.4 HYDROGEOMORPHOLOGY**

Hydrogeomorphology refers to the interacting hydrological, geological and surface processes which occur within a watercourse and its floodplain. Erosion and deposition of sediment are natural river processes that can be exacerbated by anthropogenic pressures such as land use practices and arterial drainage.

### **6.4.1 Soil Type**

Figure 6.5 overleaf illustrates the soil types that characterise HA17. The predominantly flat landscape across HA17 is reflected by the predominance of deep well drained mineral podzols with interspersed lithosols. To the north west of HA17 the Monavullagh Mountains and Knockaunapeebra Mountain are characterised by peats with the southern slopes made up of scree, peaty podzols and gleys extending within the upper reaches of the Colligan catchment which flows to Dungarvan AFA. The lands around Tramore and Environs AFA are characterised by deep gleys with marine/estuarine sediments around Back Strand within Tramore AFA.

The predominance of well drained mineral soils in HA17 is conducive to its agricultural fertility and predominance of agricultural land use. The peaty soils to the north-west would indicate relatively high susceptibility to soil erosion and can be considered a source of sediment which if accelerated due to anthropogenic pressures and given the right pathway (channel typology) can make its way to the Colligan watercourse network which drains towards Dungarvan AFA. The deep gleys in the vicinity of Tramore indicate poorly drained soils and higher potential for surface water runoff.

There is currently ongoing research in Ireland and the UK involving modelling the risk of diffuse pollution in river catchments, including sediment transport. Recent research has focussed attention on assessing risk based on erodibility and hydrological connectivity to the river network, with land use/land cover the most common measure of erodibility. While soil type clearly has an influence on erodibility, Reaney et al. (2011) argue that an emphasis upon land cover is warranted as land cover is typically correlated with soil type (refer to Section 6.4.3).

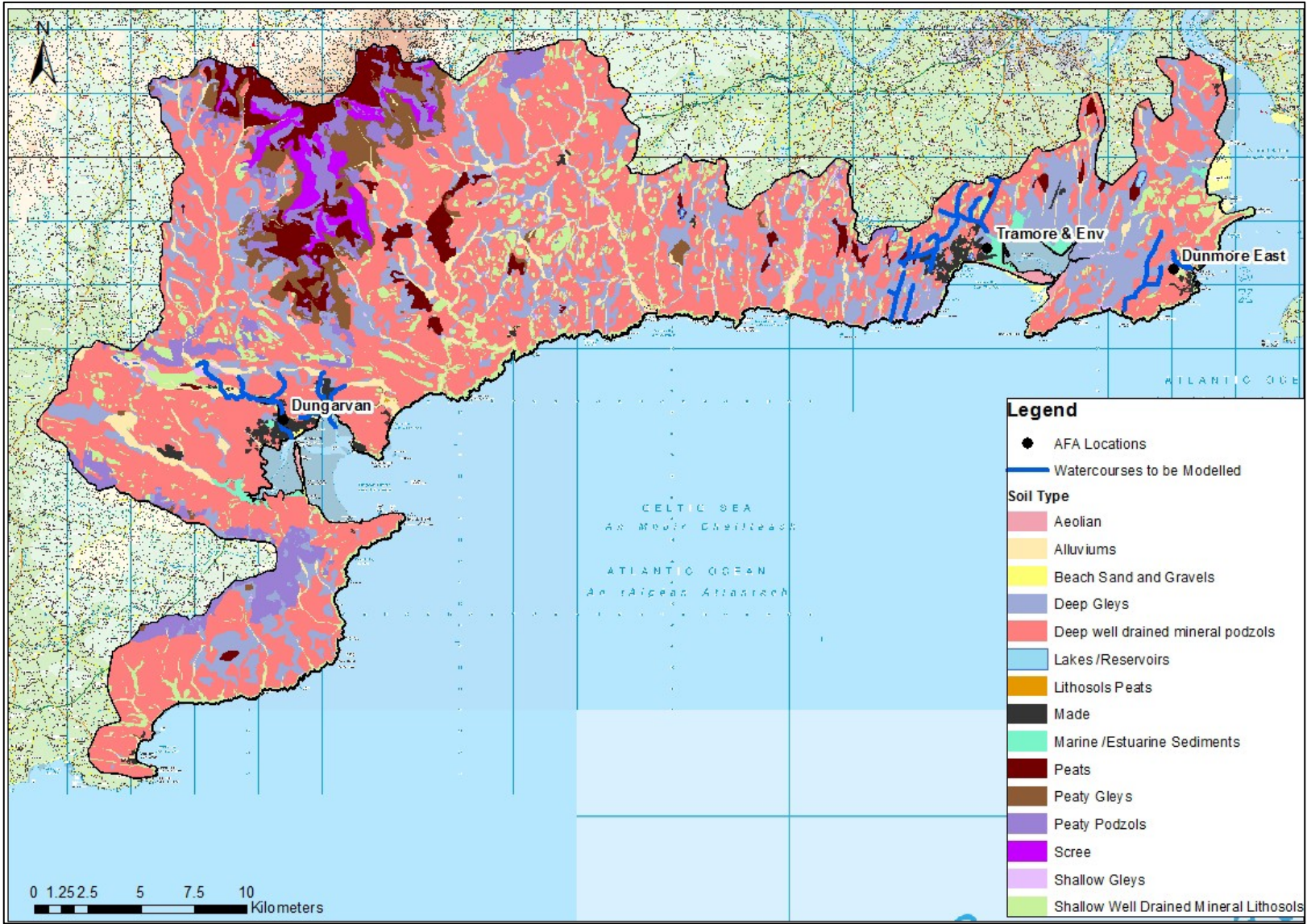


Figure 6.5: HA 17 Soil Types (Source: Irish Forest Soils Project, FIPS – IFS, Teagasc,2002)

### 6.4.2 Channel Typology

As part of national EU Water Framework Directive 2000/60/EC (WFD) studies on hydromorphology through River Basin District projects a national channel typology dataset was defined for Irish rivers<sup>2</sup>. It classified river channels into channel type at 100m node points along each reach. It is based on four key descriptors which categorise rivers according to channel type. Table 6.8 below outlines the four main channel types and how these relate to valley confinement, sinuosity, channel slope and geology.

**Table 6.8: Channel Types and Associated Descriptors**

Channel Type	Confinement	Sinuosity	Slope	Geology
<b>Step Pool / Cascade</b>	High	Low	High	Solid
<b>Bedrock</b>	High	Low	Variable	Solid
<b>Riffle &amp; Pool</b>	Low - Moderate	Moderate	Moderate	Drift / Alluvium
<b>Lowland Meander</b>	Low	High	Low	Drift / Alluvium

Typical undisturbed channel behaviour in terms of flow is described as follows for each of the channel types shown:

**Bedrock:**

- Boulders and cobbles often exposed, but few isolated pools.
- Overbank flows uncommon.
- Morphology only changes in very large floods.

**Cascade and step-pool:**

- At low flows, many of the largest particles (boulders, cobbles) may be exposed, but there should be continuous flow with few isolated pools. Valley confinement and low sinuosity associated with this channel type are conducive to erosion processes given the high energy, velocities and steepness of the channels.

**Pool-riffle:**

- Gravel bars may be exposed in low water conditions, but gravels and cobbles in riffles as well as logs and snags are mainly submerged.

<sup>2</sup> ([http://www.wfdireland.ie/docs/20\\_FreshwaterMorphology/CompassInformatics\\_MorphologyReport](http://www.wfdireland.ie/docs/20_FreshwaterMorphology/CompassInformatics_MorphologyReport))

**Lowland Meandering:**

- In low flow conditions some bars or islands may be exposed, but water fills the majority of the channel. Low valley confinement and high sinuosity associated with this channel type are conducive to sediment deposition as the river slows down, moves laterally within its floodplain and loses energy.

In the national context, HA17 is relatively small and its coastal location defines the predominance of small catchment watercourses flowing towards the sea. To the west, watercourses originate in the Monavullagh Mountains as higher energy step-pool cascade channels before becoming pool riffle through the flatter lands to the south. To the east of HA17, watercourses are generally lower slope rivers, the predominance of pool riffle channel types indicating that energy remains higher than that of a larger lowland meandering system from source to mouth. Channel type and slope for HA17 rivers are indicated in Figure 6.6 and 6.7.

As indicated by Figure 6.6, Dungarvan AFA is on the receiving end of the relatively steep step-pool cascade Colligan system with pool-riffle channels remaining as it enters Dungarvan before becoming tidally influenced at the estuary. Channel slope ranges from 0.381 (in other words 1 in 3) in the upper reaches to 0.00 (negligible gradient) at its mouth. In contrast, Tramore and Dunmore East are located on low slope river systems, but these are still characterised as pool riffle given that sinuosity is lower than that associated with larger lowland meandering systems. Channel slope generally ranges from 0.08 (1 in 13) to 0.00 (negligible gradient) here.



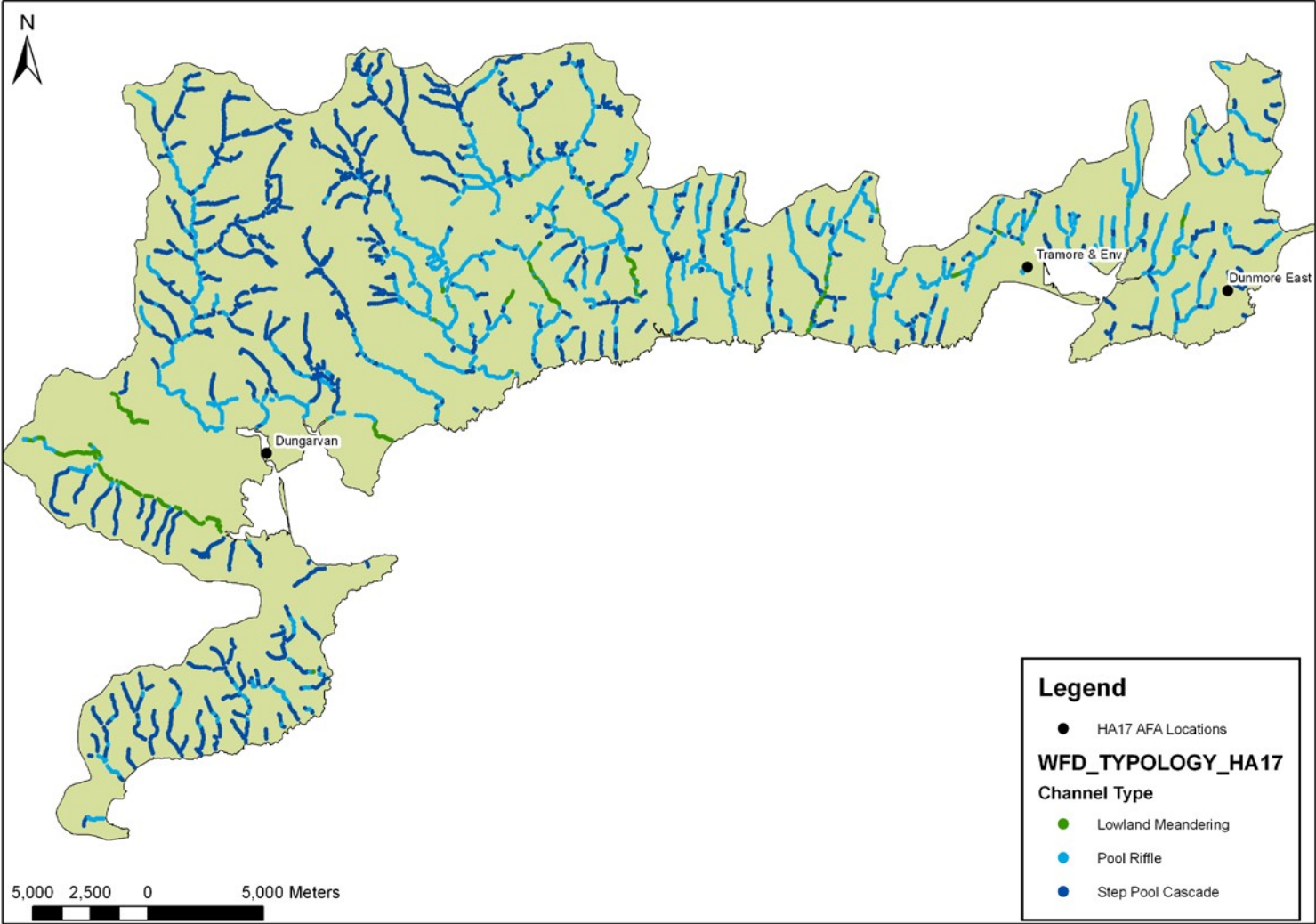


Figure 6.6: WFD Channel Typology HA17

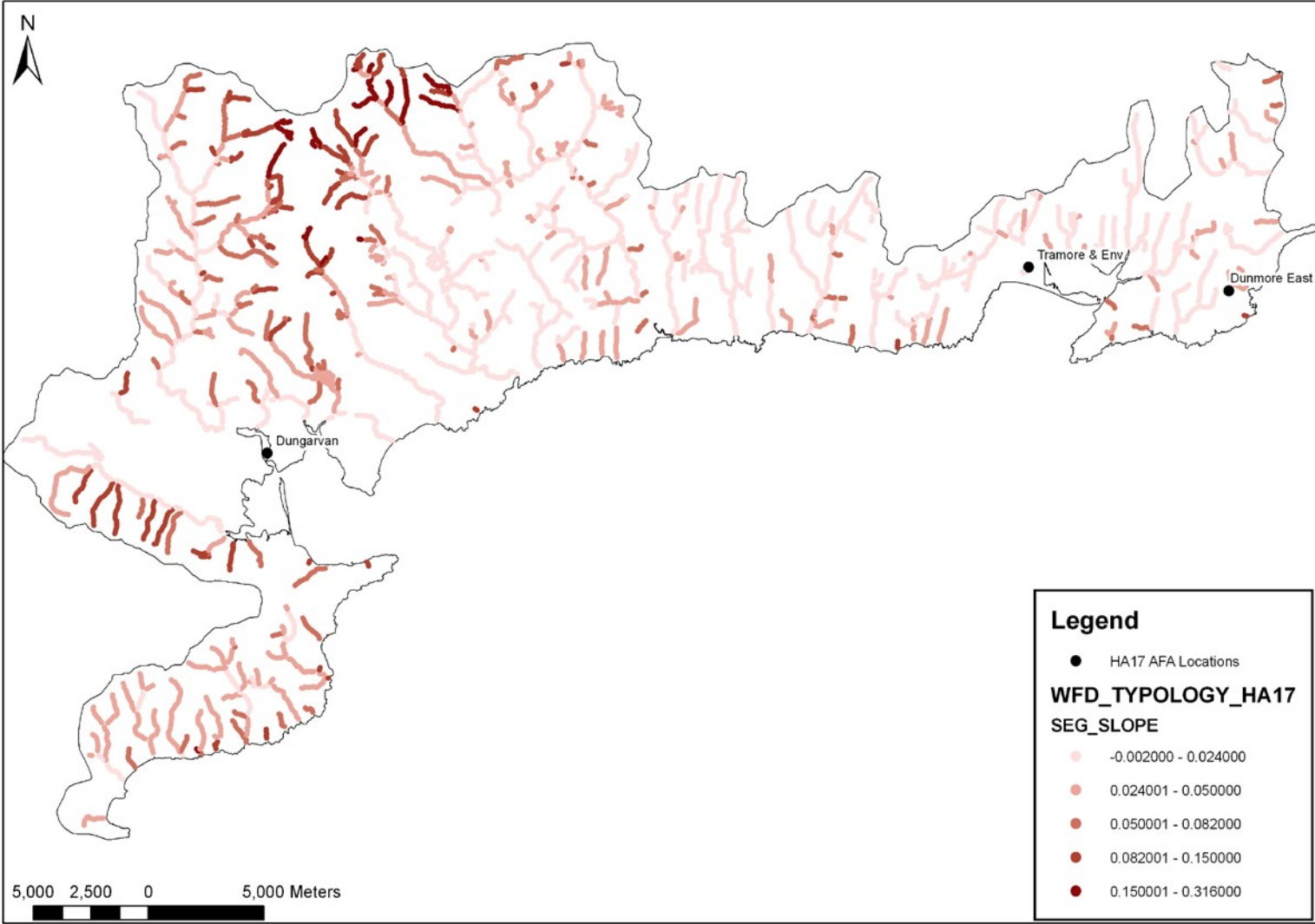


Figure 6.7: Changes in Channel Slope HA17



These channel types are typical of Irish coastal catchments. Sediment transport, erosion and deposition are natural morphological processes. It is expected that the upper reaches will be more dynamic and as the river moves to the lower lands, sediment is accumulated and transported. Sediment deposition is expected where the channel meanders and loses energy. Based on Figure 6.6 and Figure 6.7 Dungarvan AFA could be affected by sediment deposition transported from upper reaches. The watercourses flowing through Tramore and Dungarvan whilst lower in slope are still classified as pool riffle, and are smaller channels. These are less likely to be affected by sediment deposition transported from other reaches.

This only becomes an issue if too much sediment is transported from the upper reaches and deposited causing channel capacity issues or if localised damage occurs to flood defence structures from scour.

### **6.4.3 Land Use and Morphological Pressures**

Figure 6.8 illustrates the land use types within HA17. It is essentially a rural catchment with 62% pasture coverage and 10% arable land. Forestry accounts for almost 10% of the catchment area (coniferous, broadleaf, mixed and transitional), while peat bogs account for 6%. Forestry and peat bogs are located in the north-west Monavullagh Mountains. Urban fabric makes up 2.5% of catchment area.

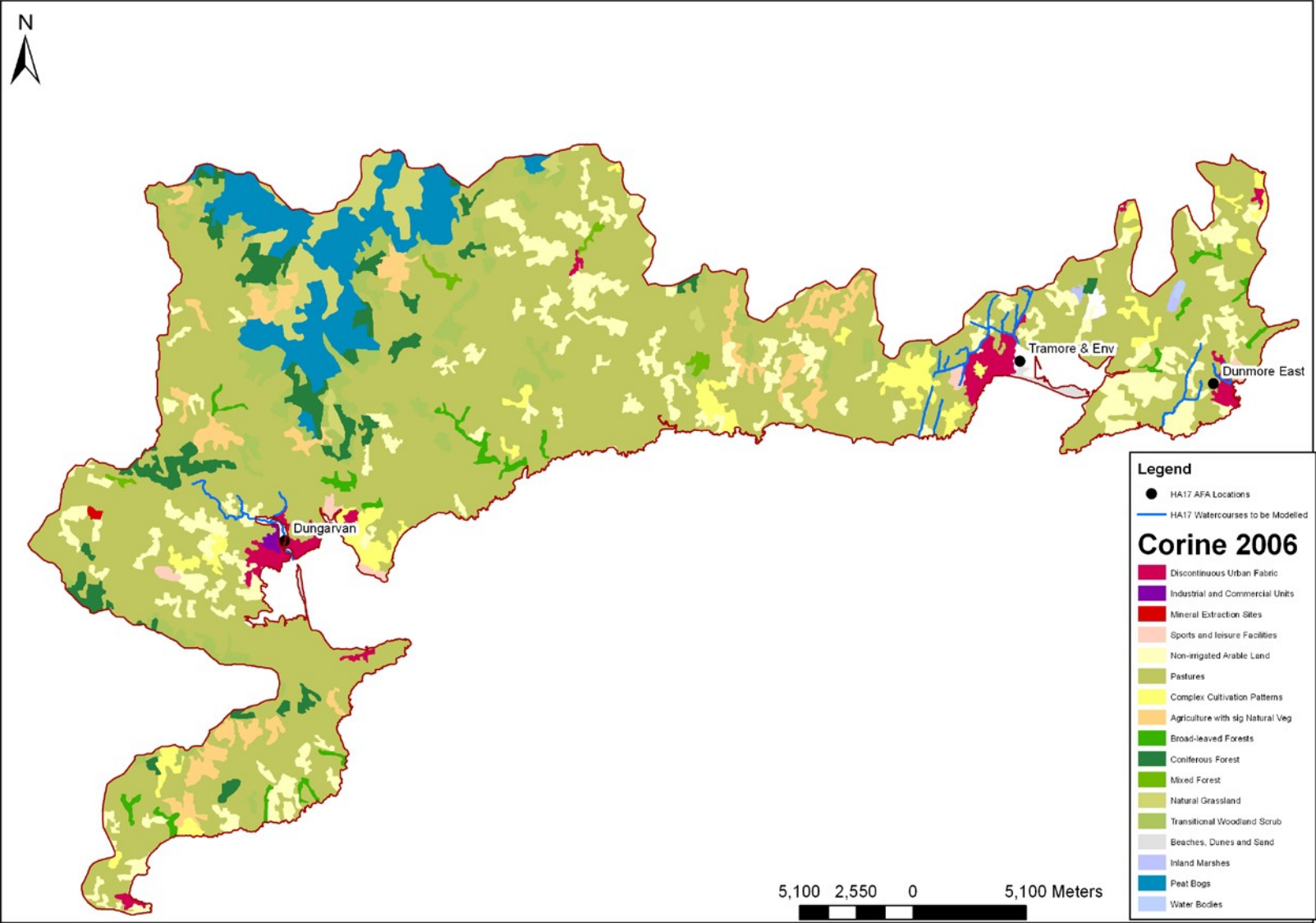


Figure 6.8: HA17 Land Use (CORINE 2006)

Drainage of bog lands and peat extraction activities potentially lead to large quantities of peat silt being discharged to the receiving waters. This may be a consideration in Dungarvan which is located downstream of the peat bogs in the Monavullagh Mountains.

However the extensive coverage of pasture (grassland) suggests that in general, the level of exposed soil is limited within the catchment. However there is a significant presence of arable land, particularly in close proximity to the modelled watercourses at Dunmore East and to a lesser extent Dungarvan as shown on Figure 6.8. Depending on agricultural practices, farming of arable land can lead to increased soil loss to receiving watercourses through ploughing and extensive exposure of soils, which will be exacerbated if environmental measures such as buffer strips along river banks are not employed. At a localised scale, this can increase flood risk due to silting up of smaller channels and loss of channel capacity, on a catchment scale the extent of arable land throughout the Study Area warrants further consideration. In addition, increased sedimentation causing scour of flood defences within AFAs must be considered.

The impact of hydro-geomorphological changes ultimately applies to the performance of flood risk management options. The impact of sediment transport and deposition will be considered further under the hydraulic modelling of options stage of the CFRAM Study for all Models since there is the potential for changes to channel capacity due to fluctuations in sediment load.

#### **6.4.4 Arterial Drainage**

A further consideration in a national context is the potential effect of arterial drainage on watercourse channel and floodplain geomorphology. The original Arterial Drainage Act, 1945 was a result of the Browne Commission which examined the issue of flooding and the improvement of land through drainage works and was mainly focussed on the agricultural context. Following flood events in the mid to late 80s the emphasis on flood management shifted to the protection of urban areas and as such the Arterial Drainage Amendment Act was passed in 1995. This widened the scope of the act to cover the provision of localised flood relief schemes. The OPW have used the Arterial Drainage Acts to implement various catchment wide drainage and flood relief schemes. Arterial drainage scheme works may consist of dredging of the existing watercourse channels, installation of field drains / drainage ditches and the construction of earthen embankments using dredged material to protect agricultural land.

The extent of the watercourses affected by arterial drainage within Ireland is captured in the FSU physical catchment descriptors defined under FSU Work Package 5.3. There are no watercourses that have been subject to arterial drainage within HA17, therefore it is not considered further in this Study.

#### **6.4.5 River Continuity**

River continuity is primarily an environmental concept relating to the linear nature of the river ecosystem and its disruption due to manmade structures such as weirs and dams which alter river flow and can impede fish migration. It is a morphological pressure which has been given consideration

under the Water Framework Directive. Any collated data is of use from a flood risk management perspective as it provides information on such structures and as such can be accounted for in terms of flow regulation in hydraulic modelling.

The risk of impassability may also be an indication of significant hydraulic control and as such is useful in hydraulic modelling. The channel and structure survey undertaken specifically for the South Eastern CFRAM Study includes full geometric survey of all manmade structures and therefore ensures their inclusion in the hydraulic modelling phase.

#### **6.4.6 Localised Pressures**

As well as the catchment based pressures discussed in this report, localised morphological changes can have an impact on channel capacity and the structural integrity of flood defences due to the effects of scour from high sediment loads within rivers. For example known areas of bank erosion within AFAs can undermine existing channel structures. At this stage of the study, data relating to such localised effects within AFAs has not been received for inclusion in this analysis. Localised areas of bank erosion caused by e.g. cattle poaching were recorded and photographed within AFAs during CFRAM Study team site audits. These are documented and will be fed into the option development process so that such localised risks in terms of channel capacity issues or adverse effects on channel structures can be mitigated. It is also recommended that Progress Group members confirm if such data is available within their organisations that could be of use in the options development process.

## 6.5 FUTURE SCENARIOS FOR FLOOD RISK MANAGEMENT

The OPW does not have a specific policy for the design of flood relief schemes but has produced a draft guidance note ‘Assessment of Potential Future Scenarios for Flood Risk Management’ (OPW, 2009). The document gives guidance on the allowances for future scenarios based on climate change (including allowing for the isostatic movement of the earth’s crust), urbanisation and afforestation. Table 1 from the guidance has been adapted for the purposes of this study to take into account catchment specific effects and is presented here as the basis (Table 6.10) for the design flow adjustment for the mid range (MRFS) and high end (HEFS) future scenarios. Refer to Chapter 7 for discussion of uncertainties associated with allowances made for extreme rainfall depths and flood flows based on recent research.

**Table 6.9 HA17 Allowances for Future Scenarios (100 year time horizon)**

	<b>MRFS</b>	<b>HEFS</b>
<b>Extreme Rainfall Depths</b>	+ 20%	+ 30%
<b>Flood Flows</b>	+ 20%	+ 30%
<b>Mean Sea Level Rise</b>	+ 500mm	+ 1000mm
<b>Urbanisation</b>	URBEXT multiplied by 2.7 <sup>1</sup> Susceptible sub-catchments URBEXT = 50% <sup>2</sup>	URBEXT multiplied by 11.8 <sup>1</sup> Susceptible sub-catchments URBEXT = 85% <sup>2</sup>
<b>Afforestation</b>	-	+ 10% Design Flow <sup>3</sup>

*Note 1: Reflects growth rates of 1% and 2.5% p.a. for mid range and high end future scenarios. To be applied to FSU URBEXT Physical Catchment Descriptor (PCD) up to a maximum of 85%.*

*Note 2: Applied to areas of sub-catchment or tributary catchment within the AFA which are susceptible to rapid urbanisation but which at present are predominantly undeveloped (i.e. growth rates applied to existing low FSU URBEXT PCD would result in an unrealistically low future scenario URBEXT).*

*Note 3: Add 10% to the Design Flow: This allows for increased run-off rates that may arise following felling of forestry*

## 6.6 POLICY TO AID FLOOD REDUCTION

Considering the projected growth in population within HA17 the main future change which could increase flood risk is urbanisation of the catchment. If not managed correctly rapid urbanisation could lead to large swathes of the catchment becoming hard paved and drained through conventional drainage systems which are designed to remove water from the urban area quickly and efficiently. This could have potentially significant implications for fluvial flooding as the flood flows in the

watercourses and rivers would intensify. Some of the smaller watercourses in particular could become prone to flash flooding if they become urbanised.

Sustainable Urban Drainage (SuDS) policy has been about for over a decade now in the UK and Ireland. It is a key concept in OPW's "The Planning System and Flood Risk Management Guidelines for Planning Authorities" as published in November 2009. The term covers a range of practices and design options that aim to replicate the pre-development surface water run-off characteristics of the undeveloped catchment following development both in terms of water quality but more importantly, from the perspective of flood risk management, in terms of run-off peak flow, intensity and volume. Typical measures include soft engineered solutions such as filter strips, swales, ponds and wetlands and hard engineered solutions such as permeable paving, 'grey water' recycling, underground storage and flow control devices. The implementation of successful SuDS requires a joined up policy that covers planning, design, construction and maintenance. One of the biggest issues surrounding SuDS implementation is long term ownership and maintenance although the long term benefits of SuDS can be shown to outweigh the costs associated with these issues.

If a comprehensive SuDS policy is implemented covering planning, implementation and maintenance, then the impacts of urbanisation on flood flows can be substantially mitigated.

## 7 SENSITIVITY AND UNCERTAINTY

Hydrological analysis and design flow estimation are probabilistic assessments which originate from observed data. The long term conditions which affect the observations, whether they are climatic or catchment based, have been shown to varying degrees to be changing over time. Further to this the degree of uncertainty within the sub-catchments analysed under the South Eastern CFRAM Study varies greatly due to the quality and availability of observed data. Factors which may affect the quality of both the analysed historic events and the estimation of the future design events are listed below:

- Hydrometric data record length and gaps
- Hydrometric data quality (classified in terms of the rating confidence under FSU WP 2.1)
- High quality meteorological data availability
- Calibration quality of hydrological models (generally a result of all of the above)
- Standard error of flow estimation (catchment descriptor based) techniques
- Future catchment changes, urbanisation, afforestation etc.
- Climate change

The above list is not exhaustive but seeks to identify the main potential sources of uncertainty in the hydrological analysis. In terms of climate change, the National University of Ireland, Maynooth recently completed a study entitled “Stress Testing Design Allowances to Uncertainties in Future Climate: The Case of Flooding” (Murphy et al, 2011). The aim of the study was to undertake a sensitivity analysis on the uncertainty inherent in estimates of future flood risk. The estimate concerned is the use of a +20% factor to increase peak flows under the MRFS. Four case study catchments were looked at, the Moy and Suck in the west, the Boyne in the East and the Munster Blackwater in the South West. The Study concluded that the inherent uncertainty associated with this +20% factor is greatest for flood events of lower AEP (higher return period), and that this has design implications for flood protection infrastructure e.g. culverts, flood defences, bridges, since they are designed for lower frequency events e.g. 1% AEP. The Study also noted that there was a variation between study catchments in the percentage change in peak flows associated with 20%, 4%, 2% and 1% AEP events under climate change compared with present day scenarios. The western catchments (Moy and Suck) experienced greater magnitudes of changes in flood frequency than those in the east (Boyne) and South West (Munster Blackwater). This would indicate a greater level of uncertainty associated with the +20% MRFS factor for climate change when applied in the west of the country. Further to these the list of factors which could potentially affect the uncertainty and sensitivity of the assessment of flood risk under the South Eastern CFRAM Study is subject to further uncertainties and sensitivities related to the hydraulic modelling and mapping stages. Examples of some of the modelling considerations which will further affect the sensitivity / uncertainty of the CFRAM Study outputs going forward from the hydrological analysis are past and future culvert blockage and survey error (amongst others). These considerations will be considered through the hydraulic modelling and mapping report along with the hydrological considerations listed here to build a complete picture of uncertainty / sensitivity of Study outputs.

It is not possible to make a quantitative assessment of all of the uncertainties as some of the factors are extremely complex. Nevertheless it is important that an assessment is made such that the results can be taken forward and built upon through the subsequent phases of the study. It is also important that the potential sources of uncertainty in the hydrological analysis and design flow estimation are flagged such that the integrated process of refining the hydrological inputs and achieving model calibration can be achieved more efficiently through a targeted approach. A qualitative assessment has therefore been undertaken to assess the potential for uncertainty / sensitivity for each of the models and is provided in this chapter (refer to Table 7.1 overleaf). The assessed risk of uncertainty is to be built upon as the study progresses through the hydraulic modelling and mapping stages. Following completion of the present day and future scenario models the assessed cumulative uncertainties can be rationalised into a sensitivity / uncertainty factor for each scenario such that a series of hydraulic model runs can be performed which will inform the margin of error in the flood extent maps.



## 7.1 UNCERTAINTY / SENSITIVITY ASSESSMENT MODEL BY MODEL

**Table 7.1: Assessment of contributing factors and cumulative effect of uncertainty / sensitivity in the hydrological analysis**

Model No.	Model Name	Uncertainty / Sensitivity – Present Day Scenario				Uncertainty / Sensitivity – Future Scenarios				Notes
		Observed Flow Data <sup>1</sup>	Simulated Flow Data <sup>2</sup>	Catchment Data <sup>3</sup>	Ungauged Flow Estimates <sup>4</sup>	Forestation <sup>5</sup>	Urbanisation <sup>6</sup>	Climate Change <sup>7</sup>	Sediment <sup>8</sup>	
1	Dungarvan	n.a.	n.a.	Medium	Medium/ High	Medium	Medium	Medium	Medium	<p>60% HEPs in HA17 not on FSU database, PCDs and catchment defined using GIS. This accounts for 33% of HEPs in Model 1. Catchments in relatively flat areas more difficult to define (Ringphuca and Duckspool).</p> <p>Ungauged model, reliance on ungauged catchment methods.</p> <p>Some HPWs are downstream of high energy channel types with peat bogs and commonage land (felled forest area). Sediment transport and deposition within HPWs to be considered.</p>
2	Tramore	n.a.	n.a.	Medium/ High	High	Low	Medium	Medium	Medium / Low	<p>60% HEPs in HA17 not on FSU database, PCDs and catchment defined using GIS. This accounts for 75% of HEPs in Model 2. Catchments in relatively flat areas more difficult to define.</p> <p>Ungauged model, reliance on ungauged catchment methods.</p> <p>Arable land uses adjacent to modelled watercourses upstream of Tramore may be a sediment source but catchment is small pool riffle so deposition may not be excessive.</p>

Model No.	Model Name	Uncertainty / Sensitivity – Present Day Scenario				Uncertainty / Sensitivity – Future Scenarios				Notes
		Observed Flow Data <sup>1</sup>	Simulated Flow Data <sup>2</sup>	Catchment Data <sup>3</sup>	Ungaaged Flow Estimates <sup>4</sup>	Forestation <sup>5</sup>	Urbanisation <sup>6</sup>	Climate Change <sup>7</sup>	Sediment <sup>8</sup>	
3	Tramore Environs	n.a.	n.a.	Medium	High	Low	Low	Medium	Low	60% HEPs in HA17 not on FSU database, PCDs and catchment defined using GIS. This accounts for 50% of HEPs in Model 3 (i.e. 1 out of 2). Catchments in relatively flat areas more difficult to define.  Ungaaged model, reliance on ungaaged catchment methods.
4	Tramore Environs	n.a.	n.a.	Medium/High	High	Low	Low	Medium	Low	60% HEPs in HA17 not on FSU database, PCDs and catchment defined using GIS. This accounts for 100% of HEPs in Model 4 (i.e. 2 out of 2). Catchments in relatively flat areas more difficult to define.  Ungaaged model, reliance on ungaaged catchment methods.
5	Dunmore East	n.a.	n.a.	Medium/High	High	Low	Medium	Medium	Medium/Low	60% HEPs in HA17 not on FSU database, PCDs and catchment defined using GIS. This accounts for 75% of HEPs in Model 5 (i.e. 3 out of 4). Catchments in relatively flat areas more difficult to define.  Ungaaged model, reliance on ungaaged catchment methods.  Arable land uses adjacent to modelled watercourses upstream of Dunmore East may be a sediment source but catchment is small and pool riffle channel so deposition may not be excessive.
6	Dunmore East	n.a.	n.a.	Medium	High	Low	Low	Medium	Medium	60% HEPs in HA17 not on FSU database, PCDs and catchment defined using GIS. This accounts for 50% of HEPs in Model 6 (i.e. 2 out of 4). Catchments in relatively

Model No.	Model Name	Uncertainty / Sensitivity – Present Day Scenario				Uncertainty / Sensitivity – Future Scenarios				Notes
		Observed Flow Data <sup>1</sup>	Simulated Flow Data <sup>2</sup>	Catchment Data <sup>3</sup>	Ungauged Flow Estimates <sup>4</sup>	Forestation <sup>5</sup>	Urbanisation <sup>6</sup>	Climate Change <sup>7</sup>	Sediment <sup>8</sup>	
										<p>flat areas more difficult to define.</p> <p>Ungauged model, reliance on ungauged catchment methods.</p> <p>Arable land uses adjacent to modelled watercourses upstream of Dunmore East may be a sediment source but catchment is small and pool riffle channel so deposition may not be excessive.</p>

<sup>1</sup> Observed flow data left as n.a. where there is no gauged data to inform the flood flow estimation for the model.

<sup>2</sup> Simulated data refers to data output from rainfall run-off models. This has not been possible in HA17 since totally ungauged.

<sup>3</sup> Catchment data refers to delineated catchment extents or catchment descriptors. Low to high reflects uncertainty in physical catchment descriptors or catchment delineation, higher risk associated where FSU nodes are not available for first derivation of HEP PCDs. May have been subject to change since FSU due to urbanisation, afforestation, arterial drainage scheme.

<sup>4</sup> Ungauged flow estimates based on FSU WP 2.3. Dependent on 1, 2 & 3 above. Where high quality gauge data is available along modelled reach upon which adjustment can be performed then uncertainty is considered low. Where no gauge data is available within catchment then certainty is considered medium to high. Uncertainty greater in smaller, urbanised catchments where ungauged estimation methodologies are considered to be more sensitive.

<sup>5</sup> See Section 6.2 Considered to be low risk of uncertainty to hydrological analysis in HA17 with the exception of Dungarvan.

<sup>6</sup> See Section 6.3 Considered generally to be a medium risk of uncertainty to hydrological analysis with higher risk in smaller urban tributaries.

<sup>7</sup> See Section 6.1 Considered a medium risk of uncertainty to hydrological analysis in all cases due to the large range of projections and higher inherent uncertainty associated with the +20% MRFS for lower AEP events (Murphy et al, 2011).

<sup>8</sup> Sedimentation of channels causing capacity issues or localised impacts on channel structures are to be considered in options development phase of CFRAM Study. Degree of uncertainty indicated here is based on qualitative assessment of accelerated soil erosion risk due to land use pressures and pathways to watercourses. Considered under future scenarios only as present day sediment conditions are reflected by recently captured channel survey data.

## **7.2 CONCLUSIONS OF SENSITIVITY ANALYSIS**

The assessment of uncertainty and sensitivity in each category is relative within HA17. The assessment of uncertainty as being medium or high does not suggest that the analysis is poor but rather in the context of the full suite of design flow estimation techniques being employed in the South Eastern CFRAM Study that uncertainty in that category is towards the higher end of the range. All AFAs are relatively small and ungauged with 40% well defined in terms of catchment data. The ungauged flow estimates have mostly been designated as having a high uncertainty as a result yet the procedure for estimating and adjusting is in line with best practice and would be consistent with the recommended estimation methodology for a typical ungauged rural Irish catchment. The largest degree of uncertainty for the present day scenarios is attributed to the smaller ungauged catchments of which HA17 is entirely made up.

In the future scenarios climate change has been defined as potential source of medium uncertainty due to the inherent uncertainties surrounding climate change science and how these will translate into changes in fluvial flood flows in Ireland. It has not been assigned a higher risk as it is not considered to be any more uncertain than urbanisation which is generally a source of medium uncertainty in the prediction of future flood flows. Dungarvan, Tramore and Dunmore East AFAs have been attributed medium uncertainty based on observed higher growth rates and possible sensitivity to urbanisation. The complex social, cultural and economic factors which affect urbanisation are difficult to predict for a 100 year time horizon. However there is also the effect of sustainable drainage to consider which adds a further degree of uncertainty depending on the extent to which it is successfully implemented. There is a high degree of certainty that there will be little afforestation within the HA17 catchments, and as such this is only a significant source of uncertainty in Dungarvan where forestry already exists in the upper catchment.

## **8 CONCLUSIONS**

No useable hydrometric data exists within HA17 for the purposes of statistical based design flow estimation. High quality meteorological data in the form of rainfall radar is also not available for application in the hydrological analysis of the HA17 catchments, and it would not be applicable anyway since there is no hydrometric data upon which to calibrate. Given these limits, a comprehensive methodology has been applied combining the latest FSU statistically based techniques for analysis.

There is a high degree of potential uncertainty within all of the catchments since estimates of flood flow are derived from catchment descriptor based estimates and direct adjustment based on gauge data within the sub-catchment is not possible. Hydrologically similar gauging stations with high confidence in the data have been used to adjust index flow estimates at these catchments and therefore provide some improvement. However in some cases, adjustment using a pivotal site was not considered appropriate given the high degree of variability in the pivotal site options derived from pivotal site review, suggesting that no clear trend of upward or downward adjustment was correct, particularly when the results were predominantly above or below the confidence limits associated with the FSU ungauged catchment index flow regression equation. In these cases, flows were not adjusted, for example in Model 1. The calibration of the hydraulic models to historic observed/anecdotal evidence will help to screen out design flow estimates which are not reflective of the actual behaviour of these sub-catchments.

There are many potential future changes to the catchment, margins of error and uncertainties which must be considered within the study. However the cumulative application of worst case scenarios, one on top of the other could lead to erroneous flood extents which do not take into account the diminishing cumulative joint probability of these factors. For this reason this report has separated future HA17 changes that have a high degree of certainty in the projections from those changes which are less certain. Future changes which have a relatively higher degree of uncertainty, along with margins of error and other uncertainties have been risk assessed individually. This risk assessment is to be taken forward and built upon through the hydraulic modelling phase with the ultimate goal of providing a single error margin for the flood extent maps on an AFA by AFA basis. This rationalised single error margin is designed to inform end users in a practical way as to the varying degree of caution with which mapped flood extents are to be treated.

### **8.1 SUMMARY OF THE RESULTS AND GENERAL PATTERNS**

The catchment can be characterised hydrologically as follows:

- The catchment has a wide range of climatic and physiographic characteristics. The drier, lowland areas to the centre moving towards the coast have SAAR values as low as 875mm while the upper catchment to the north-west has SAAR values of up to 1450mm.

- Hydrometric data is not available within HA17 for direct use or as pivotal sites in adjusting index flow estimates using catchment descriptors. As such, hydrological modelling to supplement statistical analysis techniques has not been possible since there is no data upon which to calibrate the rainfall runoff models.
- Meteorological data is limited to rain gauge data across the catchment. The processing of rainfall data from the Dublin and Shannon Airport radar is not of benefit since it does not cover any of the Models in HA17.
- Flood behaviour when defined in terms of the growth curve, i.e. in orders of magnitude greater than the median event, on average is higher than would have been thought based on older methodologies (FSR) particularly in smaller catchments.
- The 1% AEP flood event ranges from approximately 2.0 (lower reaches of River Colligan) to 3.4 times larger than the median flood flow depending on catchment size. This compares to approximately 2 under FSR.
- Growth factor increases with decreasing catchment size.

Design flow estimation is the primary output of this study and has been developed based on the analysis contained in this report. This analysis is based on previous observed data and estimation / modelling techniques. This analysis will require further validation through the calibration of the hydraulic models. As modelling progresses there may be some elements of the hydrological analysis that might need to be questioned and interrogated further. This is reflective of best practice in hydrology / hydraulic modelling for flood risk assessment. The modelling may necessitate the adjustment of some of the design flows and as such any adjustments made will be summarised within the Hydraulic Modelling Report.

## **82 RISKS IDENTIFIED**

The main potential source of uncertainty in the analysis is due to a lack of hydrometric gauge data in HA17. This has been mitigated as much as possible by the use of a comprehensive range of analysis and estimation techniques from statistical, catchment descriptor based estimates in line with the most recent CFRAM guidance.

Following this cycle of the South Eastern CFRAM Study the main potential adverse impact on the hydrological performance of the catchments is high uncertainty associated with design flow estimation due to lack of hydrometric data and the higher uncertainty associated with estimation in small catchments.

## **8.3 OPPORTUNITIES / RECOMMENDATIONS**

This study presents a potential opportunity to improve the hydrological analysis further in the next cycle of the South Eastern CFRAM Study:

1. No hydrometric gauging stations were identified for rating review in HA17 – there are two stations within HA17 where it is advised by EPA Hydrometrics that ratings are poor and unreliable (17001 at Kilmacthomas and 17002 at Fox's Castle, records since 1976). It is worth pursuing the improvement of these gauges by considering rating review of existing data, additional spot gaugings, or infrastructure improvements where needed. These stations are not located on any of the watercourses to be modelled in this Study but could serve as preferred pivotal sites in index flow adjustment if their reliability was improved.
2. Recommending that new gauging stations are installed on all of the ungauged models (or branches of models) is a long term goal but probably unrealistic within the timeframe of this or even the next CFRAM Study cycle. Multiplied up nationally this would lead to a long list of gauging stations which would likely remain unrealised at a time when many organisations are rationalising their existing networks and may even obscure the case for those gauging stations which are more acutely needed. A more focussed exercise to identify the most acutely needed gauging stations would be more effectively undertaken following hydraulic modelling and consultation such that the AFAs which are at greatest risk, are most affected by uncertainty in the design flow estimates and which would significantly benefit from additional calibration data are identified as priorities. As such it is recommended that this exercise is undertaken following the hydraulic modelling stage. In the interim improvements to the existing hydrometric gauge network should focus on improving the ratings through the collection of additional spot flow gaugings at flood flows at existing stations (refer to bullet point 1 above). Furthermore there is a shortage nationally of very small and / or heavily urbanised catchment gauge data and as such new gauging stations on this type of catchment, ideally within a CFRAM Study AFA, could be progressed immediately.

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**APPENDIX A**

**HA17 HYDROMETRIC DATA STATUS TABLE**

HA17 HYDROMETRIC DATA STATUS TABLE

Station Name	Station ID	1975	1976	1977	1978	1979	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	Station ID	Provider
KILMACTHOMAS	17001																																						17001	Waterford Co Co
FOX'S CASTLE	17002																																						17002	Waterford Co Co
COLLIGAN WOOD	17003																																						17003	Waterford Co Co
SHANBALLY	17004																																						17004	Waterford Co Co
WOODHOUSE	17005																																						17005	Waterford Co Co
BALLYLANEEN	17006																																						17006	Waterford Co Co
KNOCKMAON	17007																																						17007	Waterford Co Co
DUNHILL CASTLE BR.	17008																																						17008	Waterford Co Co
POULNASKEHA	17010																																						17010	Waterford Co Co
DUNMORE EAST	17061																																						17061	OPW
CARRIGAVANTRY RESERVOIR	17090																																						17090	Waterford Co Co

Key

	Annual Max Data
	Daily Data
	15 Min Data

## **APPENDIX B**

### **DESIGN FLOWS FOR MODELLING INPUT**

**Model 1 - Dungarvan (inc. Duckspool & Sallybrook)**

Node ID_CFRAMS	AREA (km <sup>2</sup> )	Q <sub>med</sub> (m <sup>3</sup> /s)	Flows for AEP								Model number
			50% (2)	20% (5)	10% (10)	5% (20)	2% (50)	1% (100)	0.5% (200)	0.1% (1000)	
17_278_4_RPS	80.846	28.34	28.34	36.16	41.74	47.66	56.42	63.99	85.49	96.86	Model 1
17_277_1_RPS	4.511	1.86	1.86	2.68	3.31	4.01	5.10	6.09	9.15	10.88	Model 1
17_277_3_RPS	4.758	1.58	1.58	2.28	2.82	3.41	4.34	5.19	7.78	9.26	Model 1
Top-up between 17_277_1_RPS & 17_277_3_RPS	0.247	0.10	0.10	0.14	0.18	0.21	0.27	0.32	0.49	0.58	Model 1
17_830_1_RPS	1.517	0.68	0.68	0.99	1.22	1.47	1.87	2.24	3.36	4.00	Model 1
17_830_4_RPS	2.953	0.95	0.95	1.37	1.68	2.04	2.60	3.10	4.66	5.54	Model 1
Top-up between 17_830_1_RPS & 17_830_4_RPS	1.436	0.65	0.65	0.94	1.15	1.40	1.78	2.13	3.19	3.80	Model 1
17_832_2_RPS	108.439	33.12	33.12	42.26	48.78	55.71	65.94	74.78	99.92	113.20	Model 1
Top-up between 17_278_4_RPS & 17_832_2_RPS	19.882	6.12	6.12	7.81	9.01	10.29	12.18	13.82	18.46	20.92	Model 1
17_303_1_RPS	11.587	4.92	4.92	7.09	8.74	10.59	13.48	16.10	24.17	28.74	Model 1
17_645_1	3.219	1.81	1.81	2.60	3.21	3.89	4.95	5.92	8.88	10.56	Model 1
17_645_2_RPS	5.532	2.16	2.16	3.12	3.85	4.66	5.93	7.09	10.64	12.65	Model 1
Top-up between 17_645_1 & 17_645_2_RPS	2.313	1.04	1.04	1.50	1.85	2.24	2.84	3.40	5.10	6.07	Model 1
17_1001_US	0.251	0.08	0.08	0.12	0.15	0.18	0.23	0.28	0.42	0.50	Model 1
17_1001_Inter1	1.466	0.50	0.50	0.72	0.89	1.08	1.37	1.64	2.46	2.92	Model 1
Top-up between 17_1001_US & 17_1001_Inter1	1.215	0.42	0.42	0.60	0.75	0.90	1.15	1.37	2.06	2.45	Model 1
17_1001_Inter2	1.668	0.63	0.63	0.91	1.12	1.36	1.73	2.06	3.09	3.68	Model 1

Top-up between 17_1001_Inter1 & 17_1001_Inter2	0.202	0.09	0.09	0.13	0.15	0.19	0.24	0.29	0.43	0.51	Model 1
17_1001_Trib	1.732	0.65	0.65	0.94	1.16	1.40	1.79	2.14	3.20	3.81	Model 1
Top-up between 17_1001_Inter2 & 17_1001_Trib	0.064	0.03	0.03	0.04	0.05	0.06	0.08	0.10	0.15	0.17	Model 1
17_303_DS	21.541	7.54	7.54	10.86	13.40	16.23	20.65	24.68	37.04	44.04	Model 1
Top-up between 17_303_1_RPS & 17_303_DS	2.69	1.07	1.07	1.55	1.91	2.31	2.94	3.51	5.27	6.27	Model 1

Node ID_CFRAMS	AREA (km <sup>2</sup> )	MRFS Flows for AEP								HEFS Flows for AEP			Model number
		50% (2)	20% (5)	10% (10)	5% (20)	2% (50)	1% (100)	0.5% (200)	0.1% (1000)	10% (10)	1% (100)	0.1% (1000)	
17_278_4_RPS	80.85	35.37	45.14	52.11	59.50	70.43	79.87	106.72	120.91	70.42	107.95	163.40	Model 1
17_277_1_RPS	4.51	2.32	3.35	4.13	5.00	6.37	7.61	11.42	13.58	5.58	10.28	18.35	Model 1
17_277_3_RPS	4.76	1.98	2.85	3.52	4.26	5.42	6.47	9.72	11.56	4.32	7.95	14.20	Model 1
Top-up between 17_277_1_RPS & 17_277_3_RPS	0.25	0.12	0.18	0.22	0.27	0.34	0.40	0.61	0.72	0.27	0.50	0.89	Model 1
17_830_1_RPS	1.52	0.85	1.23	1.52	1.84	2.34	2.79	4.19	4.99	1.86	3.43	6.13	Model 1
17_830_4_RPS	2.95	1.18	1.70	2.10	2.55	3.24	3.87	5.81	6.91	2.58	4.76	8.49	Model 1
Top-up between 17_1830_1_RPS & 17_830_4_RPS	1.44	1.42	2.05	2.53	3.06	3.90	4.65	6.98	8.31	3.73	6.88	12.28	Model 1
17_832_2_RPS	108.44	41.34	52.75	60.90	69.54	82.31	93.35	124.73	141.31	74.82	114.69	173.61	Model 1
Top-up between 17_278_4_RPS & 17_832_2_RPS	19.88	8.59	10.95	12.65	14.44	17.09	19.39	25.90	29.34	26.38	40.44	61.21	Model 1

17_303_1_RPS	11.59	6.14	8.85	10.91	13.22	16.83	20.10	30.17	35.88	14.75	27.17	48.49	Model 1
17_645_1	3.22	2.26	3.25	4.01	4.86	6.18	7.39	11.08	13.18	5.42	9.98	17.81	Model 1
17_645_2_RPS	5.53	2.91	4.20	5.18	6.28	7.99	9.54	14.32	17.03	10.18	18.74	33.45	Model 1
Top-up between 17_645_1 & 17_645_2_RPS	2.31	1.57	2.26	2.79	3.38	4.30	5.14	7.71	9.17	5.11	9.42	16.81	Model 1
17_1001_US	0.25	0.14	0.20	0.25	0.31	0.39	0.46	0.70	0.83	0.37	0.69	1.23	Model 1
17_1001_Inter1	1.47	1.01	1.46	1.80	2.18	2.77	3.31	4.97	5.91	1.95	3.59	6.40	Model 1
Top-up between 17_1001_US & 17_1001_Inter1	1.22	0.85	1.22	1.51	1.83	2.33	2.78	4.17	4.96	1.63	3.01	5.37	Model 1
17_1001_Inter2	1.67	1.14	1.64	2.03	2.46	3.13	3.74	5.61	6.67	2.20	4.05	7.23	Model 1
Top-up between 17_1001_Inter1 & 17_1001_Inter2	0.20	0.16	0.23	0.28	0.34	0.43	0.52	0.78	0.92	0.30	0.56	1.00	Model 1
17_1001_Trib	1.73	1.18	1.70	2.10	2.55	3.24	3.87	5.81	6.91	2.28	4.20	7.49	Model 1
Top-up between 17_1001_Inter2 & 17_1001_Trib	0.06	0.05	0.08	0.10	0.12	0.15	0.18	0.26	0.31	0.10	0.19	0.34	Model 1
17_303_DS	21.54	9.41	13.55	16.72	20.26	25.78	30.81	46.23	54.98	43.34	79.84	142.49	Model 1
Top-up between 17_303_1_RPS & 17_303_DS	2.69	2.35	3.38	4.17	5.06	6.44	7.69	11.54	13.72	6.17	11.37	20.29	Model 1


Input flows

Top-up flows. These flows should be entered laterally

Check flows. Modellers should check to make sure these flows are being reached at each HEP

Some of these flows may be put in at the US point due to a small difference between US & DS flows.



### Model 2 – Tramore

Node ID_CFRAMS	AREA (km <sup>2</sup> )	Q <sub>med</sub> (m <sup>3</sup> /s)	Flows for AEP								Model number
			50% (2)	20% (5)	10% (10)	5% (20)	2% (50)	1% (100)	0.5% (200)	0.1% (1000)	
17_706_1_RPS	1.02	0.37	0.37	0.53	0.65	0.79	1.01	1.20	1.43	2.15	Model 2
17_730_U	0.13	0.05	0.05	0.07	0.09	0.10	0.13	0.16	0.19	0.28	Model 2
17_730_1	0.66	0.22	0.22	0.32	0.39	0.47	0.60	0.72	0.86	1.28	Model 2
Top-up between 17_730_U & 17_730_1	0.53	0.18	0.18	0.26	0.32	0.38	0.49	0.58	0.70	1.04	Model 2
17_34_U	0.09	0.03	0.03	0.05	0.06	0.07	0.09	0.11	0.13	0.20	Model 2
17_34_1	0.28	0.10	0.10	0.14	0.17	0.21	0.27	0.32	0.38	0.57	Model 2
Top-up between 17_34_U & 17_34_1	0.19	0.07	0.07	0.10	0.12	0.15	0.19	0.22	0.26	0.40	Model 2
17_585_U	0.05	0.02	0.02	0.03	0.04	0.04	0.06	0.07	0.08	0.12	Model 2
17_580_1	0.82	0.31	0.31	0.45	0.56	0.68	0.86	1.03	1.23	1.84	Model 2
Top-up between 17_585_U & 17_580_1	0.77	0.30	0.30	0.43	0.53	0.64	0.82	0.97	1.16	1.74	Model 2
17_42_U	0.02	0.01	0.01	0.01	0.01	0.01	0.02	0.02	0.02	0.03	Model 2
17_683_1	0.88	0.20	0.20	0.28	0.35	0.42	0.54	0.64	0.77	1.15	Model 2
Top-up between 17_42_U & 17_683_1	0.86	0.19	0.19	0.28	0.34	0.41	0.53	0.63	0.75	1.12	Model 2
17_673_U	0.17	0.04	0.04	0.06	0.07	0.09	0.11	0.13	0.16	0.24	Model 2
17_673_2_RPS	1.02	0.25	0.25	0.36	0.44	0.53	0.68	0.81	0.97	1.45	Model 2
Top-up between 17_673_U & 17_673_2_RPS	0.86	0.21	0.21	0.30	0.37	0.45	0.58	0.69	0.82	1.23	Model 2
17_379_U	0.03	0.01	0.01	0.02	0.02	0.03	0.04	0.04	0.05	0.08	Model 2
17_379_2_RPS	1.09	0.34	0.34	0.49	0.61	0.74	0.94	1.12	1.34	2.01	Model 2

Top-up between 17_379_U & 17_379_2_RPS	1.06	0.33	0.33	0.48	0.59	0.72	0.92	1.09	1.30	1.95	Model 2
17_679_U	0.15	0.06	0.06	0.08	0.10	0.12	0.16	0.18	0.22	0.32	Model 2
17_679_1	0.86	0.31	0.31	0.44	0.54	0.65	0.81	0.96	1.14	1.66	Model 2
Top-up between 17_679_U & 17_679_1	0.72	0.26	0.26	0.37	0.45	0.54	0.68	0.81	0.95	1.39	Model 2
17_485_U	0.23	0.08	0.08	0.12	0.15	0.18	0.23	0.27	0.32	0.48	Model 2
17_377_U	0.03	0.01	0.01	0.02	0.02	0.03	0.04	0.05	0.05	0.08	Model 2
17_377_1	0.08	0.03	0.03	0.05	0.06	0.07	0.09	0.11	0.13	0.19	Model 2
Top-up between 17_377_U & 17_377_1	0.05	0.02	0.02	0.03	0.04	0.04	0.05	0.06	0.08	0.12	Model 2
17_799_U	0.05	0.02	0.02	0.03	0.04	0.05	0.06	0.07	0.08	0.12	Model 2
17_799_1	0.40	0.14	0.14	0.20	0.24	0.30	0.38	0.45	0.54	0.80	Model 2
Top-up between 17_799_U & 17_799_1	0.35	0.12	0.12	0.17	0.21	0.26	0.33	0.39	0.47	0.70	Model 2
17_666_2_RPS	2.48	0.84	0.84	1.21	1.49	1.80	2.30	2.74	3.27	4.90	Model 2
Top-up between 17_485_U & 17_666_2_RPS	1.77	0.61	0.61	0.88	1.08	1.31	1.67	2.00	2.38	3.57	Model 2
17_823_2_RPS	12.81	3.91	3.91	5.64	6.96	8.43	10.72	12.81	15.27	22.87	Model 2
Top-up between 17_706_1_RPS & 17_823_2_RPS	3.70	1.22	1.22	1.76	2.17	2.63	3.35	4.00	4.77	7.14	Model 2

	Input flows
	Top-up flows. These flows should be entered laterally
	Check flows. Modellers should check to make sure these flows are being reached at each HEP Some of these flows may be put in at the US point due to a small difference between US & DS flows.

Node ID_CFRAMS	AREA (km <sup>2</sup> )	MRFS Flows for AEP								HEFS Flows for AEP			Model number
		50% (2)	20% (5)	10% (10)	5% (20)	2% (50)	1% (100)	0.5% (200)	0.1% (1000)	10% (10)	1% (100)	0.1% (1000)	
17_706_1_RPS	1.02	0.46	0.54	0.66	0.80	1.02	1.22	1.45	2.17	1.00	1.21	1.54	Model 2
17_730_U	0.13	0.06	0.01	0.01	0.02	0.02	0.02	0.03	0.04	0.13	0.24	0.43	Model 2
17_730_1	0.66	0.27	0.35	0.44	0.53	0.67	0.80	0.96	1.43	0.60	1.10	1.97	Model 2
Top-up between 17_730_U & 17_730_1	0.53	0.22	0.35	0.43	0.52	0.66	0.78	0.94	1.40	0.49	0.90	1.60	Model 2
17_34_U	0.09	0.04	0.07	0.09	0.11	0.14	0.17	0.20	0.30	0.08	0.16	0.28	Model 2
17_34_1	0.28	0.12	0.45	0.55	0.67	0.85	1.01	1.21	1.81	0.27	0.49	0.87	Model 2
Top-up between 17_34_U & 17_34_1	0.19	0.08	0.38	0.47	0.56	0.72	0.86	1.02	1.53	0.17	0.31	0.56	Model 2
17_585_U	0.05	0.03	0.02	0.03	0.04	0.05	0.06	0.07	0.10	0.06	0.12	0.21	Model 2
17_580_1	0.82	0.47	0.73	0.91	1.10	1.40	1.67	1.99	2.98	0.83	1.53	2.72	Model 2
Top-up between 17_585_U & 17_580_1	0.774	0.44	0.71	0.88	1.07	1.36	1.62	1.94	2.90	0.78	1.44	2.57	Model 2
17_42_U	0.02	0.01	0.11	0.13	0.15	0.19	0.23	0.27	0.40	0.02	0.03	0.05	Model 2
17_683_1	0.88	0.24	0.55	0.67	0.81	1.02	1.20	1.42	2.08	0.53	0.99	1.76	Model 2
Top-up between 17_42_U & 17_683_1	0.86	0.24	0.46	0.56	0.68	0.85	1.01	1.19	1.74	0.48	0.89	1.59	Model 2
17_673_U	0.17	0.05	0.15	0.18	0.22	0.28	0.34	0.40	0.60	0.11	0.21	0.37	Model 2
17_673_2_RPS	1.02	0.31	0.02	0.03	0.04	0.05	0.06	0.07	0.10	0.68	1.25	2.22	Model 2
Top-up between 17_673_U & 17_673_2_RPS	0.86	0.26	0.06	0.07	0.09	0.11	0.13	0.16	0.23	0.57	1.05	1.88	Model 2
17_379_U	0.03	0.02	0.04	0.05	0.06	0.08	0.09	0.11	0.16	0.07	0.12	0.22	Model 2
17_379_2_RPS	1.09	0.43	0.04	0.05	0.06	0.07	0.09	0.10	0.15	0.87	1.59	2.84	Model 2
Top-up between 17_379_U & 17_379_2_RPS	1.06	0.42	0.25	0.30	0.37	0.47	0.56	0.67	1.00	0.91	1.68	2.99	Model 2
17_679_U	0.15	0.09	0.25	0.31	0.37	0.48	0.57	0.68	1.02	0.30	0.53	0.91	Model 2

17_679_1	0.86	0.45	1.75	2.16	2.62	3.33	3.98	4.74	7.10	1.54	2.75	4.76	Model 2
Top-up between 17_679_U & 17_679_1	0.72	0.38	1.27	1.57	1.91	2.42	2.90	3.45	5.17	1.29	2.31	3.99	Model 2
17_485_U	0.23	0.12	7.94	9.79	11.86	15.10	18.04	21.50	32.20	0.43	0.79	1.40	Model 2
17_377_U	0.03	0.02	2.48	3.06	3.70	4.71	5.63	6.71	10.05	0.05	0.10	0.17	Model 2
17_377_1	0.08	0.05	0.07	0.08	0.10	0.12	0.15	0.18	0.26	0.12	0.22	0.40	Model 2
Top-up between 17_377_U & 17_377_1	0.05	0.03	0.04	0.05	0.06	0.08	0.09	0.11	0.16	0.07	0.14	0.24	Model 2
17_799_U	0.05	0.03	0.04	0.05	0.06	0.08	0.10	0.12	0.17	0.08	0.15	0.26	Model 2
17_799_1	0.40	0.19	0.28	0.35	0.42	0.53	0.64	0.76	1.14	0.51	0.95	1.69	Model 2
Top-up between 17_799_U & 17_799_1	0.35	0.17	0.25	0.30	0.37	0.47	0.56	0.66	0.99	0.45	0.83	1.47	Model 2
17_666_2_RPS	2.48	1.22	1.75	2.16	2.62	3.33	3.98	4.74	7.10	3.10	5.71	10.18	Model 2
Top-up between 17_485_U & 17_666_2_RPS	1.77	0.88	1.27	1.57	1.91	2.42	2.90	3.45	5.17	2.26	4.15	7.41	Model 2
17_823_2_RPS	12.81	5.59	8.06	9.95	12.05	15.33	18.32	21.84	32.70	14.56	26.82	47.87	Model 2
Top-up between 17_706_1_RPS & 17_823_2_RPS	3.70	1.75	2.52	3.10	3.76	4.79	5.72	6.82	10.21	4.55	8.37	14.94	Model 2

**Model 3 –  
Tramore  
Environs**

Node ID_CFRAMS	AREA (km <sup>2</sup> )	Q <sub>med</sub> (m <sup>3</sup> /s)	Flows for AEP								Model number
			50% (2)	20% (5)	10% (10)	5% (20)	2% (50)	1% (100)	0.5% (200)	0.1% (1000)	
17_802_U	0.003	0.002	0.002	0.002	0.003	0.003	0.004	0.005	0.006	0.009	Model 3
17_641_4_RPS	2.154	0.868	0.868	1.250	1.542	1.869	2.378	2.841	3.387	5.071	Model 3

**Model 4 Tramore Environs**

Node ID_CFRAMS	AREA (km <sup>2</sup> )	Q <sub>med</sub> (m <sup>3</sup> /s)	Flows for AEP								Model number
			50% (2)	20% (5)	10% (10)	5% (20)	2% (50)	1% (100)	0.5% (200)	0.1% (1000)	
17_648_U	0.05	0.022	0.022	0.032	0.039	0.047	0.060	0.072	0.085	0.128	Model 4
17_648_1	0.88	0.321	0.321	0.463	0.571	0.692	0.881	1.053	1.255	1.878	Model 4

Node ID_CFRAMS	AREA (km <sup>2</sup> )	MRFS Flows for AEP								HEFS Flows for AEP			Model number
		50% (2)	20% (5)	10% (10)	5% (20)	2% (50)	1% (100)	0.5% (200)	0.1% (1000)	10% (10)	1% (100)	0.1% (1000)	
17_802_U	0.00	0.00	0.00	0.00	0.00	0.01	0.01	0.01	0.01	0.00	0.01	0.01	Model 3
17_641_4_RPS	2.15	1.08	1.56	1.93	2.33	2.97	3.55	4.23	6.33	2.37	4.36	7.78	Model 3
17_648_U	0.05	0.03	0.04	0.05	0.06	0.07	0.09	0.11	0.16	0.06	0.11	0.20	Model 4
17_648_1	0.88	0.40	0.58	0.71	0.86	1.10	1.31	1.57	2.34	0.88	1.61	2.88	Model 4

### **Model 5 Dunmore East**

Node ID_CFRAMS	AREA (km <sup>2</sup> )	Q <sub>med</sub> (m <sup>3</sup> /s)	Flows for AEP								Model number
			50% (2)	20% (5)	10% (10)	5% (20)	2% (50)	1% (100)	0.5% (200)	0.1% (1000)	
17_282_U	0.061	0.02	0.02	0.04	0.04	0.05	0.07	0.08	0.10	0.15	Model 5
17_288_U	0.096	0.05	0.05	0.07	0.09	0.11	0.14	0.16	0.19	0.29	Model 5
17_288_1	0.685	0.31	0.31	0.45	0.55	0.67	0.85	1.02	1.22	1.82	Model 5
Top-up between 17_288_U & 17_288_1	0.589	0.27	0.27	0.39	0.48	0.58	0.74	0.89	1.06	1.58	Model 5
17_282_2_RPS	2.074	0.88	0.88	1.27	1.56	1.90	2.41	2.88	3.43	5.14	Model 5
Top-up between 17_282_U & 17_282_2_RPS	1.328	0.58	0.58	0.83	1.03	1.25	1.59	1.90	2.26	3.39	Model 5


Input flows

Top-up flows. These flows should be entered laterally

Check flows. Modellers should check to make sure these flows are being reached at each HEP

Some of these flows may be put in at the US point due to a small difference between US & DS flows.

### Model 6 Dunmore East

Node ID_CFRAMS	AREA (km <sup>2</sup> )	Q <sub>med</sub> (m <sup>3</sup> /s)	Flows for AEP								Model number
			50% (2)	20% (5)	10% (10)	5% (20)	2% (50)	1% (100)	0.5% (200)	0.1% (1000)	
17_186_U	0.067	0.02	0.02	0.03	0.03	0.04	0.05	0.06	0.07	0.11	Model 6
17_134_U	0.011	0.00	0.00	0.00	0.01	0.01	0.01	0.01	0.01	0.02	Model 6
17_134_2_RPS	1.226	0.31	0.31	0.44	0.54	0.66	0.84	1.00	1.19	1.78	Model 6
17_266_3_RPS	6.451	1.57	1.57	2.26	2.79	3.38	4.30	5.14	6.13	9.18	Model 6
Top-up between 17_186_U & 17_266_3_RPS	5.158	1.27	1.27	1.83	2.26	2.74	3.49	4.17	4.97	7.44	Model 6

	Input flows
	Top-up flows. These flows should be entered laterally
	Check flows. Modellers should check to make sure these flows are being reached at each HEP
	Some of these flows may be put in at the US point due to a small difference between US & DS flows.

Node ID_CFRAMS	AREA (km <sup>2</sup> )	MRFS Flows for AEP								HEFS Flows for AEP			Model number
		50% (2)	20% (5)	10% (10)	5% (20)	2% (50)	1% (100)	0.5% (200)	0.1% (1000)	10% (10)	1% (100)	0.1% (1000)	
17_282_U	0.06	0.04	0.06	0.07	0.09	0.11	0.13	0.16	0.24	0.12	0.21	0.38	Model 5
17_288_U	0.10	0.10	0.14	0.17	0.21	0.26	0.31	0.37	0.56	0.18	0.34	0.60	Model 5
17_288_1	0.69	0.60	0.87	1.07	1.29	1.65	1.97	2.35	3.51	1.16	2.13	3.80	Model 5
Top-up between 17_288_U & 17_288_1	0.59	0.52	0.75	0.93	1.12	1.43	1.71	2.04	3.05	1.00	1.85	3.30	Model 5
17_282_2_RPS	2.07	1.70	2.44	3.02	3.65	4.65	5.56	6.62	9.92	3.27	6.02	10.74	Model 5
Top-up between 17_282_U & 17_282_2_RPS	1.33	1.12	1.61	1.99	2.41	3.06	3.66	4.36	6.53	2.15	3.96	7.07	Model 5
17_186_U	0.07	0.02	0.03	0.04	0.05	0.06	0.08	0.09	0.14	0.05	0.09	0.17	Model 6
17_134_U	0.01	0.00	0.01	0.01	0.01	0.01	0.01	0.02	0.03	0.01	0.02	0.04	Model 6
17_134_2_RPS	1.23	0.40	0.58	0.71	0.86	1.09	1.31	1.56	2.33	1.14	2.10	3.75	Model 6
17_266_3_RPS	6.45	1.94	2.80	3.45	4.18	5.32	6.36	7.58	11.35	4.24	7.81	13.94	Model 6
Top-up between 17_186_U & 17_266_3_RPS	5.16	1.57	2.27	2.80	3.39	4.32	5.16	6.15	9.20	3.44	6.34	11.31	Model 6


Input flows

Top-up flows. These flows should be entered laterally

Check flows. Modellers should check to make sure these flows are being reached at each HEP

Some of these flows may be put in at the US point due to a small difference between US & DS flows.



