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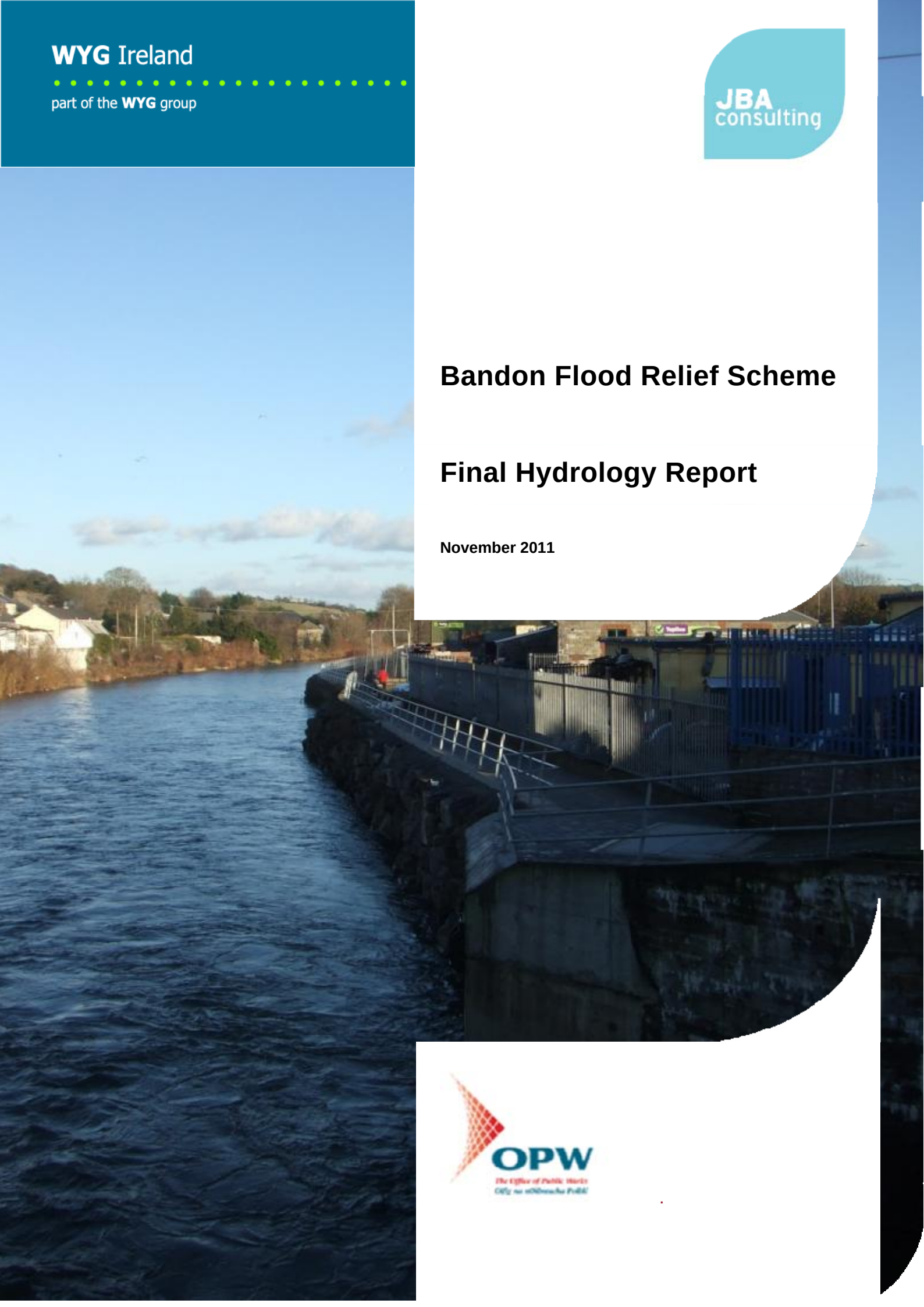
Bandon Flood Relief Scheme

Final Hydrology Report

November 2011



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Contract

This report describes work commissioned by the Office of Public Works, under the Bandon Flood Relief Scheme, by a letter dated 3rd December 2010. OPW's representative for the contract was Michael Collins. Elizabeth Russell and Wolfram Schlüter of JBA Consulting carried out this work.

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Purpose

This document has been prepared as a hydrology report for the Office of Public Works. JBA Consulting accepts no responsibility or liability for any use that is made of this document other than by the Client for the purposes for which it was originally commissioned and prepared.

Acknowledgments

The OPW provided considerable data, including river flows and levels and historic accounts of flooding. The EPA also provided information on river gauges.

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Executive Summary

WYG Ireland and JBA Consulting were commissioned by the Office of Public Works (OPW) to assess the flood risk within Bandon Town and develop a flood relief scheme and other measures to manage this risk. This hydrology report is one of a series being produced under the first stage of the project.

Bandon Town, in County Cork, has a long history of serious flooding. Flooding is primarily due to high flows in the River Bandon exceeding the channel capacity. Surface water flooding associated with heavy rainfall and exceedance of the drainage system is also a problem, particularly on Bridewell River. This is being addressed under a separate study. It is reported that river levels can be exacerbated by high tides in the River Bandon estuary, approximately 6km to the east of the town. The interaction of the tide and river flows will be investigated through the hydraulic modelling study.

The highest recorded flooding in the town occurred in November 2009. Serious flooding has also occurred in the town in 1975, 1978, 1982, 1986, 1988, 2004, 2005 and 2006. A smaller flood event occurred following commencement of this study, in January 2011. Analysis of these and other historical floods has been undertaken. The Gringorten analysis gives a return period of approximately 160 years for the 2009 flood event.

The focus of the study is Bandon town, and rivers which will be included in the hydraulic model are the River Bandon, the Bridewell River and one of its tributaries (unnamed) and the Mill Stream. The model will extends past Inishannon to the tidally dominated estuary and will include the Brinny River and the Inishannon River. Design flows have been estimated for 17 Hydrological Estimation Points (HEPs) along the rivers. The HEPs at the upstream end of each watercourse will be fixed inflows, and the others along the watercourses are check flow points. The study will aim to calibrate the modelled flows to approximate the estimated flows at each of the HEPs.

A review of the rain and flow gauges within the catchment has been undertaken, and the two gauges in and downstream of Bandon have been the subject of a detailed rating review. Both gauges are 15 minute recording level gauges. The OPW had expressed a low level of confidence in the rating equations at the two gauges, particularly for flows above QMED. The results of the rating reviews have been used to update the rating equations for the two gauges, and has resulted in changes to the flows associated with recorded levels. Using the modelled rating at gauge 20001, in Bandon town, makes a significant difference to AMAX values, reducing many of them. This has the effect of reducing QMED at the site from 148 to 122 m^3/s. This brings QMED for the two sites much more into line, now being at 122 m^3/s for 20001 and 129.5 m^3/s for 20002; very close in ratio that would be anticipated on relative catchment areas. The revised flows have been used as the basis for the design flood estimation.

It should be noted that the hydrological design flow estimation is closely linked to the hydraulic model development. The robustness and sensitivity of the flow estimates have been tested and reported on as part of the hydraulic analysis and are presented in the hydraulics report.

A range of methods were used to estimate design flows, including the Flood Studies Report and the Flood Studies Update (FSU). In this study the methods of the FSU have been selected to provide the design flow estimation for this study.

It is recommended that the GEV distribution, as derived from the single site analysis, is adopted as the growth curve for the design flows. It should be noted that design flows in excess of the 100 year return period have been extrapolated and significantly exceed the record length at Bandon (which is 50 years) and should be treated with caution. The proposed design flows are shown in Table Ex1 overleaf.

Based on the updated rating curve, the flood event of November 2009 is estimated at 414m^3/s, which, based on the design flows is estimated to be around the 1 in 200 year return period event (HEP04). This is in good agreement with the results of the Gringorten analysis of 160 year return period.

Table Ex1 - Scheme Design flows

Return Period	Growth Factor (GEV)	HEP01	HEP02	HEP03	HEP04	HEP05	HEP06	HEP07	HEP08	HEP09	HEP10	HEP11	HEP14	HEP15	HEP16	HEP17
2	1.00	116	117	4.9	122	4.3	0.7	3.0	129	14.4	135	1.5	2.8	1.6	15.2	1.0
5	1.33	155	155	6.5	162	5.7	1.0	4.0	172	19.1	180	2.0	3.7	2.1	20.2	1.4
10	1.60	186	187	7.8	194	6.9	1.2	4.9	206	23.0	216	2.4	4.4	2.5	24.3	1.6
50	2.37	276	277	11.5	288	10.2	1.8	7.2	306	34.1	320	3.6	6.6	3.8	35.9	2.4
100*	2.79	325	326	13.6	339	12.0	2.1	8.5	360	40.2	377	4.2	7.7	4.4	42.3	2.9
200*	3.28	382	383	16.0	399	14.1	2.4	10.0	423	47.2	443	4.9	9.1	5.2	49.7	3.4
1000*	4.73	551	553	23.0	575	20.3	3.5	14.4	610	68.1	639	7.1	13.1	7.5	71.7	4.8
* Return Period exceeds record lengths and data should be treated with caution																

The recommended design flows were compared to the annual maximum flow series at gauging station 20001. This comparison is a simple test showing whether the numbers of exceedances for the relevant return periods are plausible, i.e. for the 50 years of data record the 5 year return period is expected to be exceeded approximately 10 times. Findings show that the design flows of the 2, 5 and 10 year return period would have been exceeded 26, 9 and 4 times respectively. This comparison provides a good estimate for the expected exceedance intervals of 26, 10 and 5 times for the 2, 5 and 10 year return period, respectively.

Factorial Standard Error (FSE) is a measure used to describe uncertainty. This has been assessed with regards to the estimation of the mean annual flood, the growth curve and the rating curve. The uncertainty with regards to the mean annual flood was found to be relatively low (±8%) due to the long data record available at the Bandon Gauge. The uncertainty relating to the rating curve was estimated using the detailed hydraulic model and findings showed a similar level of uncertainty of ±15%. As expected, the uncertainty regarding the growth curve outweighs the aforementioned uncertainties significantly with an increase of the 100 year growth factor from 2.79 to 4.57 (corresponding to +64% for the 95% FSE).

In accordance with best practice guidelines the 95% FSE flows shall be adopted only when designing bridges and culverts. The scheme design flows (in addition to freeboard allowance) shall be adopted for the flood relief scheme, which typically consists of linear defences, increasing flow conveyance measures etc. The uncertainty analysis on the rating curve will be used for sensitivity testing and to inform the freeboard analysis, which is reported in the hydraulic modelling report.

Finally, a review of likely changes within the catchment has been undertaken, with a view to understanding how the catchment response to rainfall may change over time. Climate change, urbanisation and land use change have been identified as potential sources of change in the River Bandon catchment over the next 100 years. A review of the current land use and an assessment of the scale of likely changes indicates that only climate change is likely to impact significantly on the hydrological regime of the catchment.

Therefore, the final design flows will be increased to account for projections of increases in the statistical flow peaks to test the sensitivity of the current hydraulic regime and any potential flood management solutions. This will include testing increases of 20% and 30% on the peak flows, in accordance with OPW guidance on climate change.

In theory, changes in land management practices have the potential to offer at least partial flood management solutions. However, in reality, knowledge of the complex interactions between different practices is not complete enough to produce anything other than generic indications of potential effects. It is considered that the size of the catchment and range of opposing measures which may be implemented will limit the benefits to a localised scale.

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Abbreviations

2D	Two Dimensional (modelling)
AEP	Annual Exceedance Probability
AM	Annual Maximum
AMAX	Annual Maximum
APSR	Area of Potential Significant Risk
AREA	Area (km2)
BFI	Base Flow Index
CI	Confidence Interval
DoEHLG	Department of the Environment, Heritage and Local Government
DS	Downstream
EPA	Environmental Protection Agency
FARL	FEH index of flood attenuation due to reservoirs and lakes
FEH	Flood Estimation Handbook
FSE	Factorial Standard Error
FSR	Flood Studies Report
FSU	Flood Studies Update
GEV	General Extreme Value Distribution
GL	General Logistic Distribution
GS	Gauging Station
H2	Standardised Test Value (FEH)
HEFS	High End Future Scenario
HEP	Hydrological Estimation Point
HPW	High Priority Watercourse
ING	Irish National Grid
ISIS	Hydrology and hydraulic modelling software
JBA	JBA Consulting – Engineers & Scientists
LAP	Local Area Plan
mOD	Meters above Ordnance Datum
MPW	Medium Priority Watercourse
MRFS	Medium Range Future Scenario
OD	Ordnance Datum
OPW	Office of Public Works
POT	Peaks Over a Threshold
QBAR	Mean Annual Maximum Flood
QMED	Median Annual Flood (with return period 2 years)
QMEDrural	Median annual maximum flood in the as-rural state
RR	Rainfall-Runoff
SAAR	Standard Average Annual Rainfall (mm)
SPR	Standard percentage runoff
Tp	Time to Peak
TUFLOW	Two-dimensional Unsteady FLOW (a hydraulic model)
WRAP	Winter Rain Acceptance Potential
WYG	White Young Green

1. Introduction

1.1 Context of the Study

Bandon Town, in County Cork, has a long history of serious flooding, primarily due to high flows in the River Bandon exceeding the channel capacity. Surface water flooding associated with heavy rainfall and exceedance of the drainage system is also a problem, particularly on the Bridewell River; this is being addressed under a separate study. It is reported that river levels can be exacerbated by high tides in the River Bandon estuary, approximately 6km to the east of the town. The interaction of the tide and river flows will be investigated through the hydraulic modelling study. The highest recorded flooding occurred in November 2009. Serious flooding has also occurred in the town in 1975, 1978, 1982, 1986, 1988, 2004, 2005 and 2006. A smaller flood event occurred following commencement of this study, in January 2011. As a result, Bandon town has been identified by the OPW as an Area of Potentially Significant Risk (APSR).

Following recommendations contained in a report[1] produced following the 2009 flood event, WYG Ireland and JBA Consulting were commissioned by the Office of Public Works (OPW) to assess the flood risk within Bandon Town and develop a flood relief scheme and other measures to manage this risk. An assessment of the potential for significant increase in this risk due to climate change, ongoing development and other future pressures was also required. The whole project will comprise five stages:

- Stage I - Feasibility study and preparation of a flood risk management plan
- Stage II - Public exhibition
- Stage III - Detailed design, confirmation and tender
- Stage IV - Construction
- Stage V - Handover of works

This hydrology report is one of a series being produced under Stage I of the project.

1.2 Scope of this Report

1.2.1 Project Brief

Key tasks identified in the project brief for the hydrological analysis are:

- Review and analysis of historic floods
- Delineation of catchment boundaries
- Analysis of hydrometric and meteorological data
- Estimation of design flood parameters
- Appraisal of future environmental and catchment changes

This report details the work undertaken to complete these tasks and presents the results of the analysis.

1.2.2 Content and Key Tasks

This report provides an assessment of the flood hydrology of the River Bandon catchment, from its headwaters in the Shehy Mountains to its tidal limit at Inishannon. Details are provided regarding flow estimation locations, flow estimation methods and the flow estimates themselves. Technical calculations and decisions are provided in the appendices.

1.2.3 Report Structure

This section provides an outline of the study and a description of the River Bandon catchment. The flood history of the town is explored in Section 2 and a discussion of the

[1] WYG Ireland, Bandon Flood Relief Scheme Scoping Report, 2009

catchment boundaries and flow estimation points is provided in Section 3. The catchment hydrometric data is reviewed in Section 4, and in Section 5 the rating review for two gauges is detailed. Section 6 outlines various flow estimation methodologies and design flow estimates. Potential changes in flow regime, arising through changes in climate, land use and urbanisation are discussed in Section 6.10. The hydraulic model and model requirements are not discussed within this report; this information will be provided in a separate report.

1.3 Catchment Description

1.3.1 Overview

Digital mapping and catchment characteristics may be used to make an assessment of the likely response of rivers and tributaries during heavy rainfall events. Confidence in the assessment may be improved if hydrometric data is available for the catchment. River flow or level data, analysed in conjunction with rainfall data, can give a more accurate picture of the hydrological mechanisms operating within a catchment, and support the assessment made from catchment characteristics. The following sections of the report provide some background information on the Bandon catchment, including the main River Bandon and its tributaries, and the impact that different features may have on the response of the river to rainfall.

1.3.2 General Description

The River Bandon is located in southern County Cork, to the south-west of Cork City. The River Bandon is 56km long, and has a catchment area of over 500km^2 at its tidal limit, which is in the vicinity of Inishannon (Figure 1-1). Bandon town is located 6km upstream of Inishannon; the catchment area at this location is almost 100km^2 smaller (just over 400km^2). This difference is due to a large tributary, the Brinny River, joining the Bandon between the two towns (ING 153188, 57332).

Significant tributaries which discharge into the River Bandon upstream of Bandon Town include the Dirty, Caha, Bealanscartane and Blackwater Rivers. The River Bridewell runs through Bandon town from south to north, and joins the River Bandon just downstream of Bandon Bridge (ING 149296, 55074). A second tributary, known as the Town Park Stream, joins the River Bandon at approximately the same location, but flowing from the north. A final tributary, the Mill Stream, joins the River Bandon from the south near the site of the old brewery at the downstream (eastern) end of Bandon town (ING 150232, 55407).

The river rises in the Maughanaclea Hills in West Cork. It flows eastwards to a point west of Caha Bridge where it turns south, before turning east again to the southeast of Dunmanway. It then flows in a broad fertile valley, with woodlands, to Bandon, and loops in an arc past Inishannon, where it flows southeast and then east, becoming an estuary and reaching the sea in Kinsale Harbour. Its total length is some 64km.

In addition to Bandon, the main settlement within the catchment is Dunmanway, located near the head of the Bandon, with Inishannon and Ballineen/Enniskeane being classed as key villages in the local area plans. There are also 17 smaller villages or village nuclei. Although not the focus of this study, established settlements which are zoned for development may impact on river flows in the future. This will be examined in more detail in Chapter 6.10.

There are two distinct aspects to the catchment upstream of Bandon Town. Upstream of Dunmanway the catchment is mountainous with poor soil conditions, significant rock outcrops and small pockets of agricultural land. The area between Dunmanway and Bandon town is generally low-lying agricultural land with good soil conditions.

1.3.3 Topography and Rainfall

West County Cork is known for higher than average rainfall when compared with the rest of the country. Average annual rainfall across the Bandon catchment ranges from 1800mm in the west to 1100mm in the east. This compares with average annual rainfall in the west of Ireland of between 1000 and 1400mm, although in many mountainous districts rainfall exceeds 2000mm per year.

The elevation of the catchment varies from in excess of 500mOD (Malin Head) in the west to approximately 2mOD near Inishannon. The valley of the River Bandon is well defined, and reasonably wide upstream of Bandon. The valley bottom slopes from an elevation of approximately 80mOD at the foot of the Nowen Hill to 15mOD in Bandon. The valley narrows somewhat downstream of Bandon to Inishannon and slopes gradually to the estuary.

1.3.4 Land Use

An examination of the Corine 2006 Landcover data shows that over 82% of the catchment is agricultural land, with 65% of that classified as pasture. Of the remaining catchment area, approximately 11% of the catchment is woodland; 1% is classified as either continuous or discontinuous urban land, comprising the four settlements highlighted above; and 5% is peat bog. The upland areas to the west and north-west of the catchment are dominated by woodland and forestry, with peat bogs occurring in the higher of these areas to the west. The land use in the catchment is illustrated in Figure 1-2.

1.3.5 Geology

An assessment of the geology of the catchment is provided in the Constraints Study for the scheme[2]. Relevant details from the constraints study have been reproduced here.

The Bandon River flows through a valley cut into rocks of the Carboniferous period. The valley floor is covered with glacial drift and alluvium. 'The Geology of South Cork'[3] indicates that the majority of the study area is underlain by the carboniferous Kinsale formation which is a grey mudstone with subordinate sandstone. This formation is defined overall as a mud-dominant succession.

In the most northerly part of the Study Area in the vicinity of the Brinny River, the formation changes from the Kinsale Formation to a small band of Old Head sandstone formation before reverting to the Kinsale Formation at the most northerly tip of the study area. The Old Head sandstone formation comprises a thick succession of grey sandstones and heterolithic bedded sandstones and mudstones.

The Geological Survey of Ireland (GSI) indicates that the subsoils in the vicinity of the Study Area are mainly made up of tills derived chiefly from Sandstones and Shales, however the subsoils in the vicinity of the River Bandon consist generally of alluvium, with outcrops and subcrops of rock present between Bandon Town and Inishannon. Downstream of Inishannon, the alluvium gives way to marine/ estuarine silts and clays. Other subsoils in the study area include made-ground in the urban centres of Bandon and Inishannon and glaciofluvial sands and gravels, downstream of Inishannon at Dromkeen. A second pocket of glaviofluvial deposits is located to the North of the study area along the Ballymahane River, a tributary of the River Brinny.

1.4 Study Area

The subject of this study is Bandon town and surrounding area, as shown in Figure 1-3. Bandon has been defined as an Area of Potential Significant Flood Risk (APSR). The extent of the APSR is approximately 5.5km^2. The boundary of the APSR is shown in Figure 1-3. Significant, or High Priority Watercourses (HPWs), identified in the Bandon APSR are the River Bandon, the Bridewell River and one of its tributaries (unnamed) and the Mill Stream. Medium Priority Watercourses (MPWs), which could give rise to existing or future fluvial flooding are defined along a longer reach of the River Bandon, which extends past Inishannon to the tidally dominated estuary. The Brinny River and the Inishannon River, both tributaries of the Bandon, are also defined as MPWs.

[2] Ryan Hanley in association with McCarthy Keville O'Sullivan (2011) Bandon Flood Relief Scheme Constraints Study
[3] Sleeman and Pracht, GSI (1994) The Geology of South Cork

Figure 1-1 - River Bandon Catchment

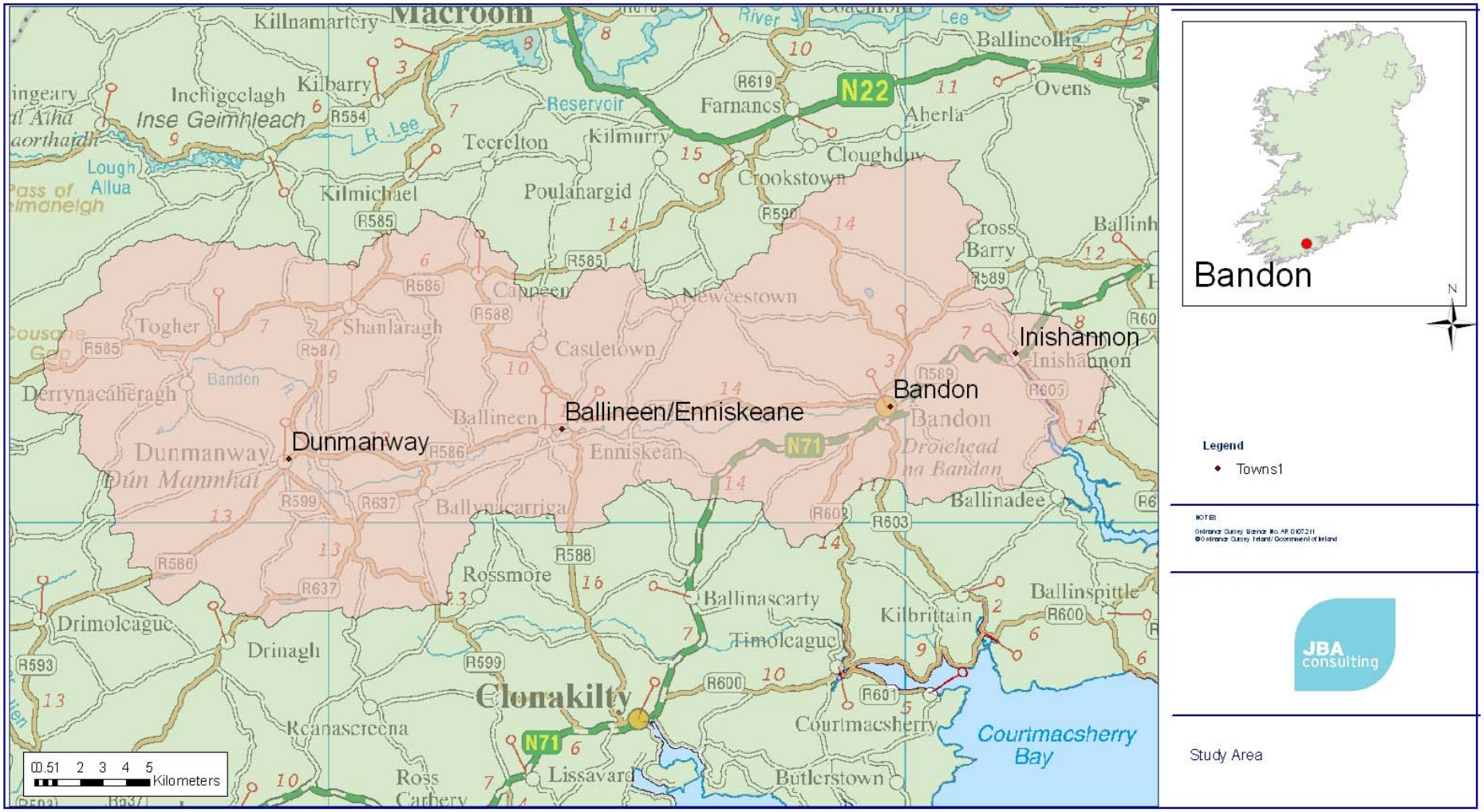


Figure 1-2 - Catchment Land Cover

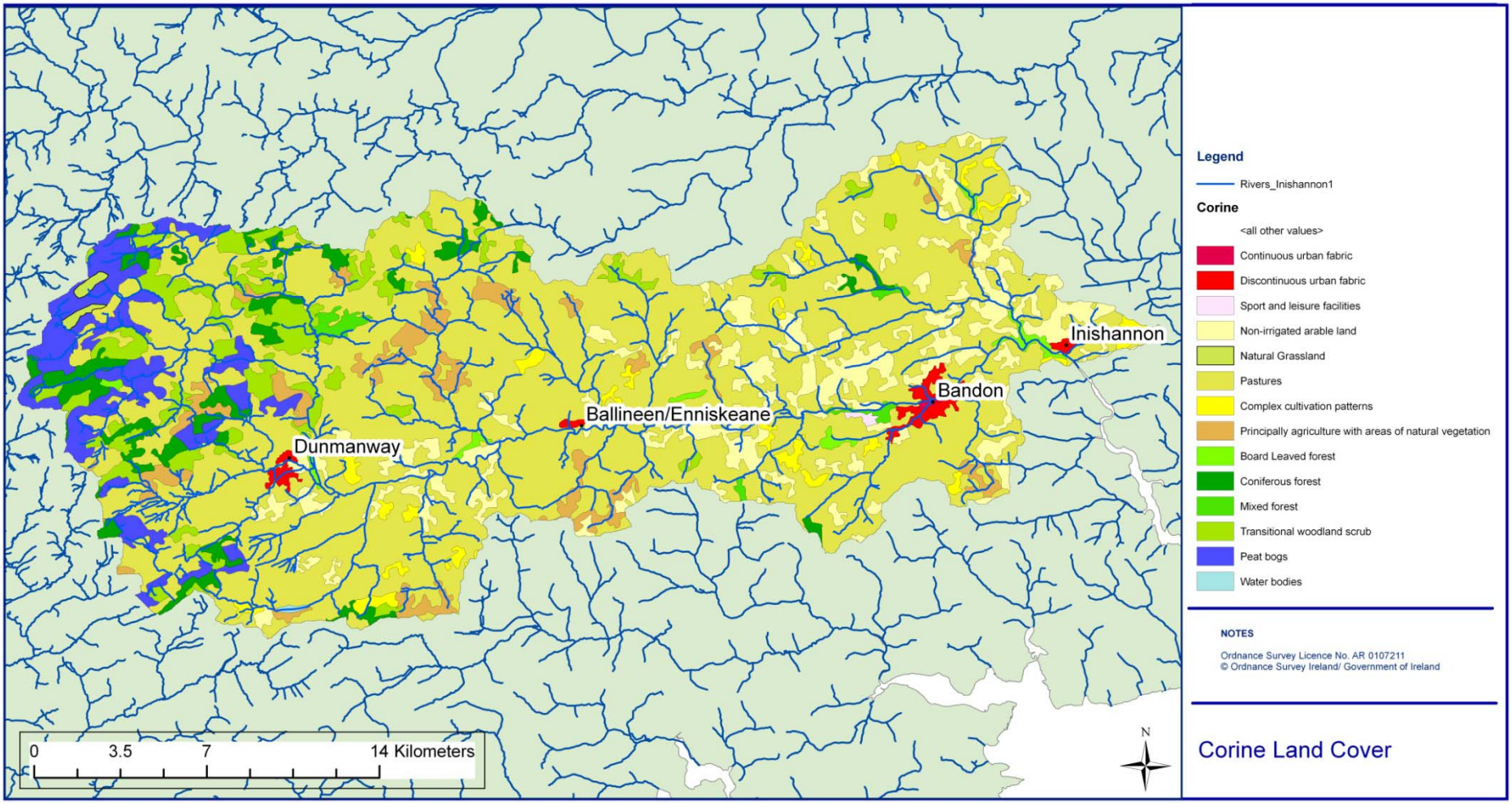
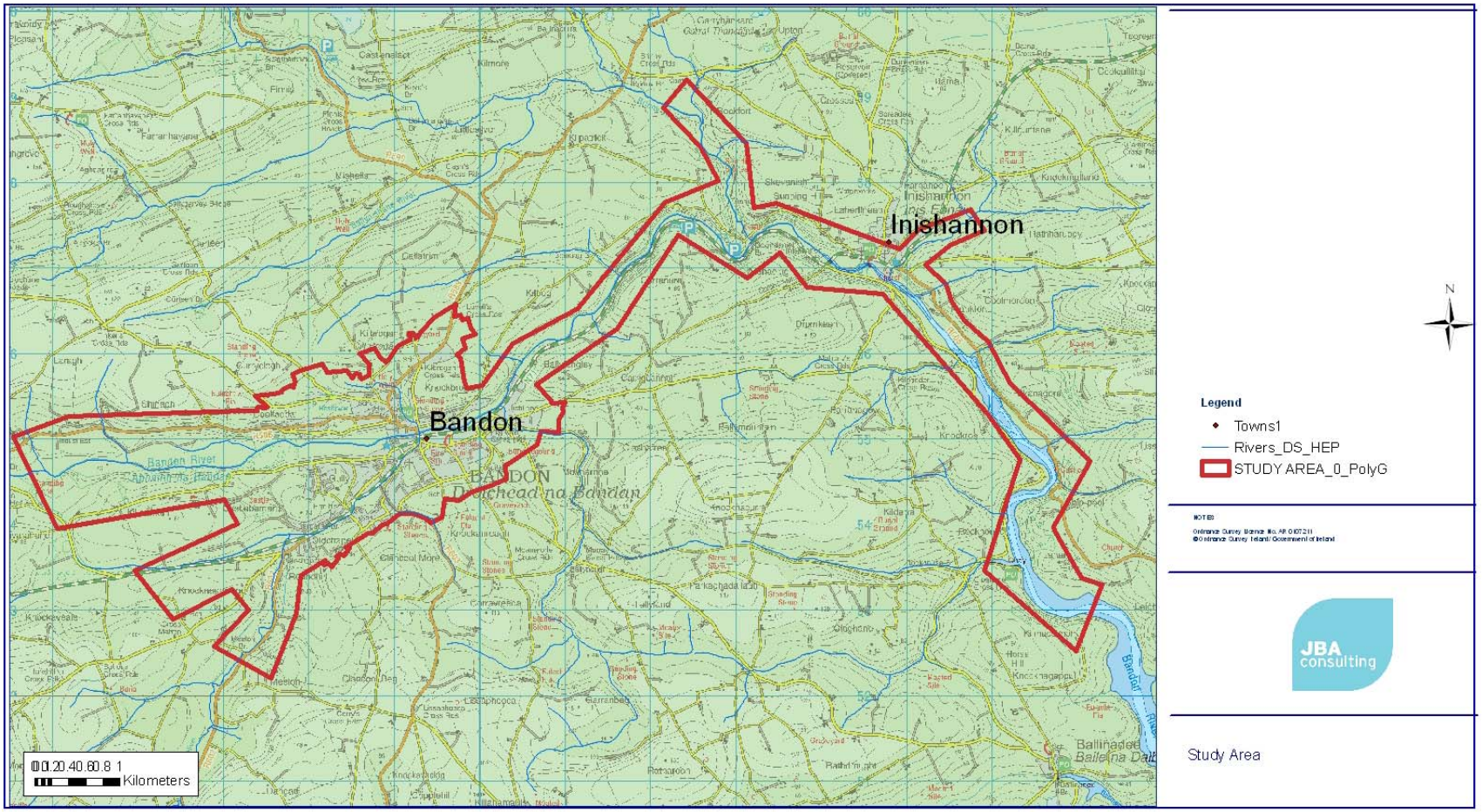


Figure 1-3 - Bandon Study Area



2. Review and Analysis of Historical Floods

2.1 Introduction

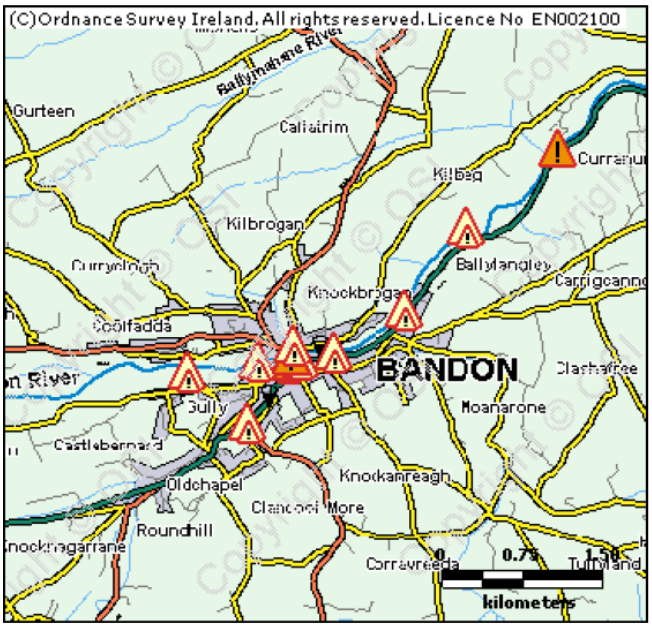
Records of past flooding are useful for looking at the sources, seasonality, frequency and intensity of flooding. Information may come from contemporary newspapers and journals, accounts of personal experiences, post-flood reports and surveys. Such historical records are mostly anecdotal and incomplete, but are useful for providing background information. A review of the flood history of Bandon is detailed in this section.

More reliable information on flooding is provided by hydrometric gauges, which are examined through hydrological assessment, as detailed in Sections 4 and 5.

2.2 Notable Flood Events

The OPW provides a national flood hazard website (www.Floodmaps.ie) that makes available information on areas potentially at risk from flooding. This website shows numerous historical flood events that have affected Bandon, as shown in Figure 2-1 below. The full map report is reproduced in Appendix A.

Figure 2-1 - Floodmaps.ie Extract



Map Scale 1:62,129

Map Legend
Flood Points
Multiple / Recurring Flood Points
Areas Flooded
Hydrometric Stations
Rivers
Lakes
River Catchment Areas
Land Commission *
Drainage Districts *
Benefiting Lands *

* Important: These maps do not indicate flood hazard or flood extent. Thier purpose and scope is explained in the Glossary.

Through examination of the historic flood record, it is clear that there is a frequent and well documented history of flooding in Bandon, as summarised in Table 2-1 During the 2009 flood event, a large area of Bandon was inundated, causing significant flood damage. This event is the most severe on record, and in the memory of the residents of the town.

Table 2-1 - Historical Flood Chronology

Date of Flood	Comment
15/01/1765	"The great flood of 15 January 1765 carried away the old Bandon Bridge" (Report on Bandon Flooding[4], 1988)
17/01/1789	Flood waters in Weir Street reached depths of 4.5' (Report on Bandon Flooding, 1988)
Pre-1916	1916 event report states - 'not within memory of the oldest inhabitant has the town of Bandon flooded to such an extent as it was on Friday'.
16-17 November 1916	Bandon flooded. Reported as being the worst flood in living memory.
10 November 1941	Bandon and Dunmanway flooded
16/17 December 1965	Flooding from the Bandon and Brinny
18-19 January 1969	Serious floods in the south of Ireland. Most seriously the Carrigrohane and Lee roads out of Cork city. Also the Innishannon-Bandon road which was impassable.
1970s and early 1980s	A report by the Hydrometric Officer (from 2005) notes: Flooding did occur regularly in the 1970s and early 80s in the centre of the town of Bandon. As far as I am aware the local authority there carried out some work. I'm not aware how successful it was, but Bandon wasn't mentioned in media reports when flooding was widespread in recent times.
1973	Details unknown, but referred to in a 1975 newspaper article
23/10/1975	Widespread flooding affecting Bandon, Inishannon, Clonakilty, Dunmanway, Skiberreen, Macroom, Cork, Monkstown, Keale Bridge. Second highest flood on record, and highest flood in 60 years (i.e. since 1916)
1976 (?)	In reports on the 1988 event, the Munster Hotel was reported to have flooded for the first time in 12 years. It is unclear if this is an approximate period, and the event was actually the same one as reported in 1975.
1978	Serious flooding noted in the WYG Scoping Report[5]
1982	Serious flooding noted in the WYG Scoping Report
05 August 1986	Widespread flooding, affecting Bandon, Bantry, Macroom, Ballyvourney, Skibbereen (Cork) Tralee, Killarney, Kenmare, Droumanassigh, Sheen (Kerry), Ennis (Clare) and other places
21-26 October 1988	Reported by a local engineer as being the "worst flooding ever seen in Bandon" (although not supported by this historical flood review or gauge records).
07/01/1996	Widespread flooding. Places affected included Cork, Clonakilty, Mallow, Fermoy, Bandon, Fountainstown, Monkstown, Kinsale (Cork), Clonmel, Carrick on Suir (Tipperary) Curracloe (Wexford)
1998	Bandon flooded.
03-Jan-99	Cork city, Silver Springs, Bandon, Middleton, Clonakilty, Bantry, Fermoy, Mallow (Cork), Clonmel (Tipperary), Caharlehren (Kerry)
2000	Widespread flooding nationwide: Churchfield Gardens & others (Cork City). Clonmel (Tipperary). Watergrass Hill & Douglas, Bandon-Clonakilty Road, Mallow, Fermoy, Blarney, Carrigaline, (Cork). Hill View Estate (Waterford City?). Counties Cork, Kerry & Limerick. Donnybrook (Dublin).
2004	Minor flooding noted in the WYG Scoping Report
2005	Minor flooding noted in the WYG Scoping Report

[4] Cork County Council, Report on Bandon Flooding, June 1988
[5] WYG Ireland, Bandon Flood Relief Scheme Scoping Report, 2009

Date of Flood	Comment
2006	Minor flooding noted in the WYG Scoping Report
19 November 2009	Most extreme flooding on record affected Bandon.
10/11 January 2011	Flooding of roads occurred in the town centre Fire brigade worked to pump water into the Bandon.

Source: **www.floodmaps.ie**, unless otherwise stated

2.3 Historical Flood Frequency

A number of previous studies have provided analysis of the historical flood events which have occurred in Bandon. A summary of these assessments is provided in the following sections. The various reports have estimated design flows along the Bandon, and the results will be used to inform the findings of this hydrology report.

2.3.1 1986 Flood Event

In a paper presented to the Institute of Engineers, Ireland (IEI) in November 1987[6], the 1986 floods of the South West region are discussed. The paper notes that a Met Éireann report estimated the rainfall between Cork airport and Tralee to be approximately a 1 in 50 year return period event, but the gauged flows were significantly less.

The event in Bandon was estimated as a 1 in 16 year return period event based on 26 years of record at Bandon gauge and a 1 in 8 year return period event based on 14 years of record at Curranure. The paper notes that 'given the very reliable nature of this record [at Bandon] and its gauging, the return period can be taken with confidence'. The discrepancy between the two gauges is attributed to the shorter period of record at Curranure. However, review of the rating curve (Section 5) has shown that the gauge is perhaps not as reliable as was thought in 1987.

2.3.2 Report on Bandon Flooding (1988)[7]

This report, by a Cork County Engineer, reviews the history of flooding in Bandon, and in particular examines the 1986 flood event. In addition to a review of the causes of flooding, and an appraisal of benefit-costs for flood protection, the report provides an analysis of the return period of events between 1961 and 1985. The results are shown in Table 2-2.

Table 2-2 - Major floods recorded in the 1988 Report on Bandon Flooding

Order of Magnitude	Date	Peak Flow (m^3/s)	Return Period (years)	Flood level at gauge (mOD Poolbeg)
1	23/10/1975	250+	50	17.17
2	6/8/1986	240	37	17.09
3	21/2/1982	204	13	16.78
4	13/12/1964	195	10	16.70
5	7/12/1978	187	8	16.62
6	15/2/1966	180	6	16.52

2.3.3 Preliminary Report (1993)[8]

The estimated design flows used in the Preliminary Report were derived from an assessment of the annual maximum floods at Bandon gauge (20001) and extrapolated using semi-log graph paper. The return periods, associated annual probability of exceedance, design flows and associated staff gauge level as derived from the 1993 report are set out in Table 2-3.

[6] Overview of the Munster flood, 5th and 6th of August, 1986. Paper presented to IEI Nov 1987. Downloaded from **www.floodmaps.ie**

[7] Cork County Council, Report on Bandon Flooding, June 1988

[8] The Preliminary Report for Bandon Sewerage Scheme Stage 2 (1993) - Flood Study by Flood Study Group, University College Cork.

Table 2-3 - Flows derived in 1993 Preliminary Report

Return Period (years)	AEP (%)	Flow (m^3/s)	Staff Gauge Level (m)
10	10	205	2.91
25	4	240	3.21
50	2	270	3.46
100	1	298	3.68
200	0.5	326	3.89
300	0.33	342	4.01

2.3.4 Scoping Report (2009) [9]

One of the aims of the 2009 Scoping Report was to give an approximation of the November 2009 flood event return period based on currently available data. Within the study, several approaches were used to provide an estimate of return periods. Firstly, the data contained in the 1993 Report was plotted on semi-log paper. Extrapolation from the graph indicated an annual exceedance probability of 1 in 550 (0.182% AEP) for the November 2009 event. However, this was based on an assessment which used gauge data to 1993; at the time of the November 2009 flood event, an additional 16 years of flow record was available. Evidence from the flood chronology indicates that there were a number of significant peak flows in this period. These factors suggest there may be a degree of uncertainty associated with a simple extrapolation of the 1993 data, and indicates the return of 1 in 550 years associated with the 2009 event should be used as a broad indication only.

An alternative assessment, also reported on in the 2009 Scoping Report, used the 20001 gauging station information up to and including 2009 to apply the Log Pearson III method. The data extrapolated from the plotted graph for the larger events are shown in the table below.

Table 2-4 - Log Pearson Method

Return Period (years)	AEP (%)	Staff Gauge Level (m)
25	4	3.3
50	2	3.6
100	1	3.8
200	0.5	4.1
300	0.33	4.2
500	0.2	4.4
1000	0.1	4.7

The above assessment indicates that the November 2009 event had a return period of approximately 1 in 300 years (0.33% AEP) based on the staff gauge reading of 4.22m at the Bandon gauge.

2.3.5 Gringorten Analysis

The flood chronology for Bandon has been used to make an estimate of the severity of the floods (return period) using the Gringorten formula:

Pr = (T+0.12) / (i-0.44) Where r is rank and N is the record length.

Although the return period from a Gringorten analysis is based only on the relative ranking and not the severity of flood events, it has the advantage of including evidence of events which pre-date the gauged record.

[9] WYG Ireland (2010), Bandon Flood Relief Scheme Scoping Report

Table 2-5 - Gringorten Ranking

Year	Bandon Gauge Peak level (staff datum) (m)	Rank of event	Approx. Return period since 1765
1765	Un-recorded	1	437
1789	Un-recorded	3	95
1916	Un-recorded	4	68
1964	2.85	11	23
1966	2.69	15	16
1968	3.23	6	44
1975	3.3	5	53
1978	2.74	13	19
1982	2.97	9	28
1986	3.10	8	32
1988	3.23	7	37
1989	2.70	14	18
2005	2.87	10	25
2009	4.21	2	157
2011	2.85	11	23

The Gringorten analysis was undertaken based on peaks over threshold (POT) analysis of the gauge record. References to three historical floods (pre-dating the gauge record) have also been used. The earliest reported event occurred in 1765 which was noted to have washed away the Bandon Bridge. Not other indication of the severity of this event can be found. Secondly, a large event was recorded as having occurred in 1789. The water depth in Weir Street is given as 4.5' (approximately 1.3m). Although water levels for the 2009 event have not been recorded in the same location, depths in Bandon town during the 2009 event reached up to 1.5m in South Main Street. The 1916 also ranked as a significant flood event. It was subsequently reported that the 1975 event was "the worst flooding since 1916"[10]. On consideration of the evidence, it was decided to rank the 2009 event between the 1765 and 1789 events. Table 2-5 shows the return periods of the 15 highest ranking flood events based on 245 years of flood history.

The Gringorten analysis gives a return period of approximately 160 years for the 2009 flood event. However, as there was uncertainty over the ranking of the earliest two events, further investigation into the significance of the top three ranking demonstrated possible return periods of in excess of 100 for the 2009 event.

2.3.6 Gauge Analysis

The rating review discussed in Section 5 of this report demonstrates that the current rating equations are unreliable; they have been updated as part of the hydraulic modelling undertaken for this study. The update has changed the flows associated with the level record, which in turn will impact on the return periods associated with the historical flood events. The revised flows for selected design events, and key historical flood events, are presented in Section 5.

[10] Cork Examiner, 24 October 1975, source www.floodmaps.ie

3. Catchment Boundaries

3.1 Hydraulic Model Extents

Levels of current and potential future flood risk, and various flood management options are being determined through hydraulic modelling. The details of the hydraulic model development will be provided in an accompanying report. When carrying out a hydrological assessment it is important to define the reaches of river that will be modelled. The extents of the hydraulic model are detailed in Section Table 3-1.

Table 3-1 - Modelled Watercourse Extents

Watercourse	Priority	Upstream Limit	Downstream Limits	Comments
Bandon	MPW	145380, 54746	147783, 54971	Upstream of the Bandon HPW
Bandon	HPW	147783, 54971	150503, 55927	Through Bandon town.
Bandon	MPW	150503, 55927	156832, 53026	Downstream of the Bandon HPW
Bridewell	HPW	147568, 53015	149296, 55074	DS limit is confluence with the Bandon
Bridewell Trib (unnamed)	HPW	147206, 53686	147770, 53897	DS limit is confluence with the Bridewell
Mill Stream	HPW	150710, 55088	150232, 55407	DS limit is confluence with the Bandon
Brinny	MPW	152325, 58847	153188, 57332	DS limit is confluence with the Bandon
Inishannon	MPW	155612, 57497	154787, 56894	DS limit is confluence with the Bandon

3.2 Hydrological Estimation Points

The project brief specified locations of 13 Hydrological Estimation Points (HEPs) along the River Bandon and its tributaries. These points are located at the upstream limits of the hydraulic model, at the junction of tributaries and at a number of other key points along the River Bandon. The location and a brief description of the HEPs is provided in Table 3-2, and illustrated in Figure 3-1. For each of the points, a catchment has been delineated based on the Ordnance Survey's National Height Model. The catchments have been reviewed and cross checked against those given as catchment descriptors under the Flood Studies Update programme[11].

In addition to the 13 specified HEPs, this study has identified a further four catchments to be included as input to the hydraulic model. These additional catchments are identified as points 14 to 17 in Table 3-2. It should also be noted that no flow estimation was undertaken for HEP 12 and 13, which are in the tidal reaches of the Bandon River, downstream of Inishannon, as no catchment descriptors are available for these HEPs.

The HEPs at the upstream end of each watercourse will be modelled as fixed inflows, and the others along the watercourses are check flow points. The study will aim to calibrate the modelled flows to approximate the estimated flows at each of the HEPs.

[11] Compass Geomatics (2009) Work Package 5.3 - Preparation of Digital Catchment Descriptors, Flood Studies Update

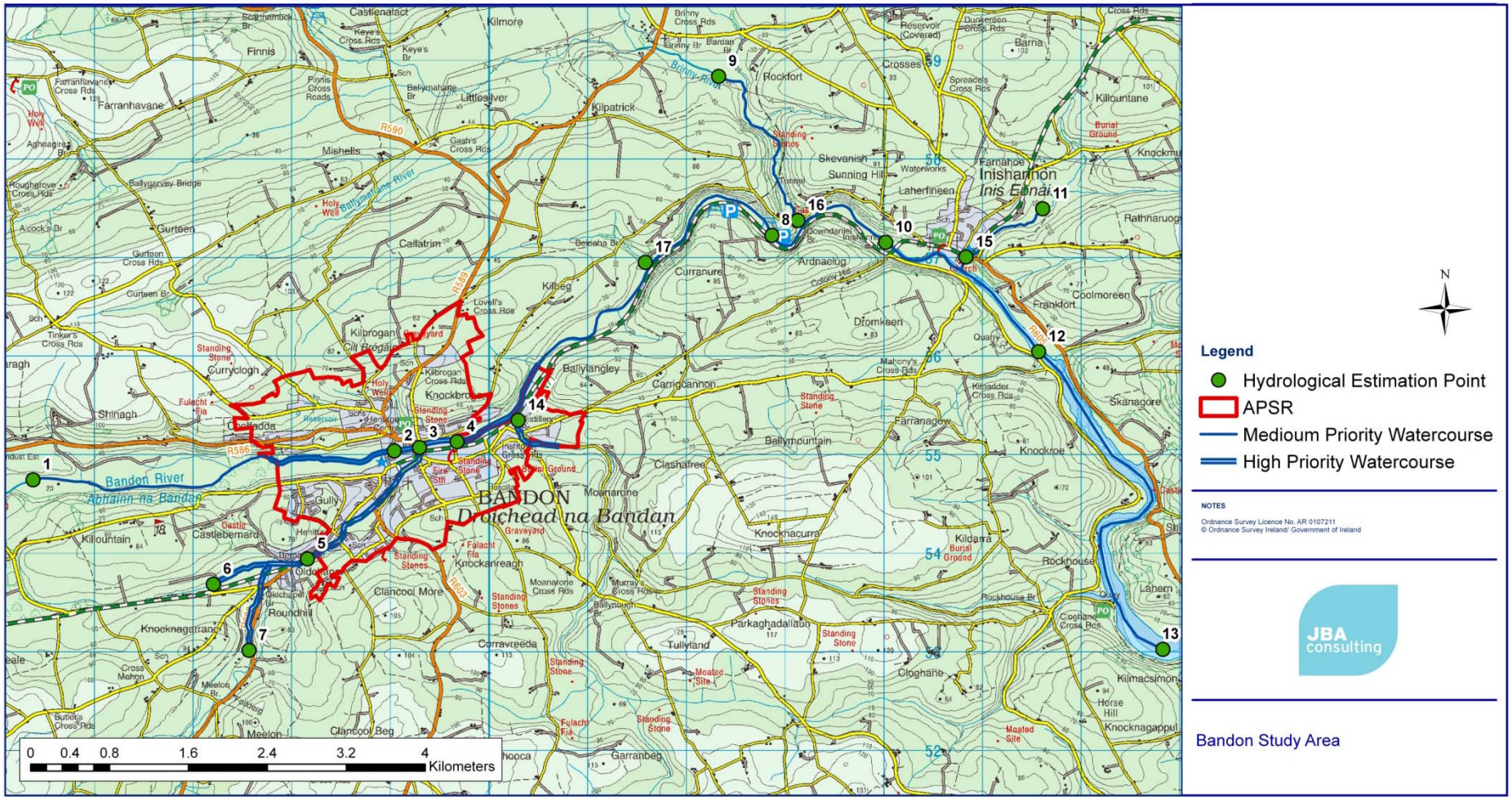
Table 3-2 - Hydrological Estimation Points

HEP	Coordinates		Watercourse	Description
1	145380	54746	Bandon	Upstream modelled limit
2	149040	55040	Bandon	Bandon town
3	149296	55074	Bridewell	Downstream modelled limit
4	149676	55132	Bandon	Downstream of Bandon gauging station (20001)
5	148160	53943	Bridewell	Downstream of junction with unnamed tributary
6	147206	53686	Unnamed tributary of the Bridewell	Upstream modelled limit
7	147568	53015	Bridewell	Upstream modelled limit
8	152868	57226	Bandon	Curranure gauging station (20002)
9	152328	58838	Brinny	Upstream modelled limit
10	154021	57155	Bandon	Inishannon gauging station (20003) - obsolete
11	155613	57495	Inishannon	Upstream modelled limit
12	155571	56045	Bandon	Downstream of Inishannon
13	156832	53026	Bandon	Downstream modelling limit
14	150296	55349	Mill Stream	Downstream end of watercourse
15	154835	57005	Inishannon	Downstream end of watercourse
16	153133	57376	Brinny	Downstream end of watercourse
17	151584	56951	Beidaha	Downstream end of watercourse

3.3 Lateral Catchments

Lateral catchments provide inflows to the hydraulic model from intervening areas between the flow estimation points. These inflows are from non-point sources such as overland flow, urban runoff or watercourses that are too small to be included as a sub-catchment. Inflows from lateral catchments tend to be adjusted during the modelling phase of mapping studies to ensure that they correspond with the hydrological estimates at the flow estimation points. Where there are inflows of particular note, such as a significant tributary, the lateral inflow to the model will be weighted to reflect this and applied at cross-sections between the corresponding HEPs. Input locations and weightings will be determined during the modelling phase and detailed in the draft report.

Figure 3-1 - Hydrological Estimation Points



4. Analysis of Hydrometric Data

4.1 Overview

The estimation of design flows is arguably the most important part of a flood study, in that it can have the largest influence on the final flood outline. However, it can also be the greatest source of uncertainty, and it is widely accepted that flow estimates may be greatly improved with the use of local hydrometric data. This chapter details the availability of hydrometric data within the study catchment, and reviews the quality of the data sets likely to be used for flood estimation. All flood estimation is based, however indirectly, on measurements of river flow and/or rainfall. The quantity and quality of hydrometric data therefore is a major factor determining the quality of the flood estimates.

4.2 Rainfall Data

Met Éireann raingauges are located in Bandon and Dunmanway. A substantial length of record is available in Dunmanway, with gauges having been in operation since 1948. The Bandon gauge was established in October 2010 therefore the record at this gauge is very short. However, all the raingauges record daily total rainfall only, and are therefore not suitable for investigating the catchment response to an individual (sub-daily) rain event.

Table 4-1 - Raingauges in the Bandon Catchment

Location	Period of Record
Bandon WWTP	Oct 2010 - present
Dunmanway (Demesne)	1980 - present
Dunmanway (Keelaraheen)	2000 - present
Dunmanway (obsolete)	1950 - 1995
Dunmanway (obsolete)	1948 - 1997

4.3 River Data

The OPW and Cork County Council (CCC) both have a number of flow and level gauges within the River Bandon catchment. There are also a number of closed (obsolete) level gauges, which were used for water quality monitoring in the past. Summary information related to each of the gauges in the catchment is provided in Table 4-2 and the locations are shown in Figure 4-1. More detailed discussions on the gauges are provided in Appendix B.

4.4 Stations for Review

Of the numerous gauging stations on the River Bandon, two have been highlighted by the OPW for a detailed review of the ratings, 20001 and 20002. The findings of the review are presented Section 5.

Table 4-2 - Hydrometric Gauges

StatNo	Watercourse	Location	Grid Reference	Operator	Status	Record Period	Comments
20001	Bandon	Bandon		OPW	Active Permanent	1960 - to date	Gauge has been the subject of a detailed rating review (Section 5)
20002	Bandon	Curranure		OPW	Active Permanent	1974 - to date	Gauge has been the subject of a detailed rating review (Section 5)
20003	Bandon	Inishannon	153784, 57329	CCC	Inactive staff gauge		This gauge is within the modelled reach of the River Bandon, lying within a MPW. The gaugings cover a similar range to the OPW continuous recorder 20002.
20004	Bandon	U/S Manch Bridge	127802, 51894	CCC	Inactive staff gauge	1977-1988 (20 gaugings)	Little available data, and gauge is located upstream of the modelled reach. Not used in study.
20007	Bandon	Ballineen	134283, 53872	CCC	Inactive staff gauge	1989-1990 (2 gaugings)	Little available data, and gauge is located upstream of the modelled reach. Not used in study.
20008	Bandon	Long Bridge Dunmanway	132410, 52900	OPW	Active Permanent	1990 - to date	Although it is a continuous recorder, it is of limited use to the study as it is so far upstream of the study area.
20010	Blackwater	Carrigmore	131733, 53404	CCC	Inactive staff gauge	1979-2009 (73 gaugings	Little available data, and gauge is located upstream of the modelled reach. Not used in study.
20011	Brinny	Downdaniel Bridge.	153129, 57380	CCC	Staff gauge	1975-present (78 gaugings)	This gauge is within the modelled reach of the River Bandon, lying within a MPW. The gaugings may be used to assist in the calibration of the model.
20013	Bandon	Carbery m.p.	132998, 53714	CCC	Inactive staff gauge	1982-1999 (32 gaugings)	Limited data, and the gauge is located a considerable distance upstream of the modelled reach; this gauge will not be considered further.
20014	Bridewell	Clockmasimon	149019, 54663	CCC	Inactive staff gauge	1990-1995 (24 gaugings)	The gauge is currently inactive and the zero datum level is unknown. The gauge will therefore not be used in the study.
20015	Bandon	Ardcahan Bridge	124321, 55734	OPW	Active Permanent	1990 - to date	The gauge is located in the upper portion of the catchment, and is upstream of the modelled reach within Bandon, but may be used a member of a pooling group for the development of a local growth curve.
20016	Bandon	Bealaboy Bridge	125599, 51282	OPW	Active Permanent	1990 - to date	The gauge is located in the upper portion of the catchment, and is upstream of the modelled reach within Bandon, but may be used a member of a pooling group for the development of a local growth curve.

Figure 4-1 - Hydrometric Gauging Stations

5. Hydrometric Gauging Station Rating Review

5.1 Overview

The rating review assessment of gauge 20001 and 20002 has been undertaken in tandem with the hydraulic modelling and findings are presented in this section.

5.2 Gauge 20001 (Bandon)

5.2.1 Gauge description

The gauging station on the River Bandon is located at grid reference W 495 551 (ING) approximately 280m downstream of Bandon Bridge. The gauge record is 50 years long, and began in December 1960. The catchment area to the gauge is approximately 400km^2.

The cross-section profile is open channel, with levels measured in a stilling well, as shown in Figure 5-1.

The OPW provided the following comments on the gauge:

- Spot measurements have been taken up to 81.0m^3/s; all of these measurements are within bank.
- Any flow estimates made above this value have been derived from an extrapolation of the within bank rating.
- The flood at Bandon peaked at 4.22m stage on 19th Nov 2009; the flow at Bandon goes out of bank at just over 2.50m SG.
- There was significant out of bank flow in Bandon during the November 2009 event.
- Some change in the stage discharge relationship is evident over time. However, this is difficult to define with any confidence due to the lack of high flow measurements. The flow estimates for Bandon do not show the level of correlation with Curranure that would be expected. The fact that the flow estimate for the November event at both sites is quite close is purely coincidental.

Figure 5-1 - Measurement section at Bandon Gauge

5.2.2 Gauge Datum

The height of gauge zero to national datum has changed a number of times since the gauge was established in 1960 (Table 5-1).

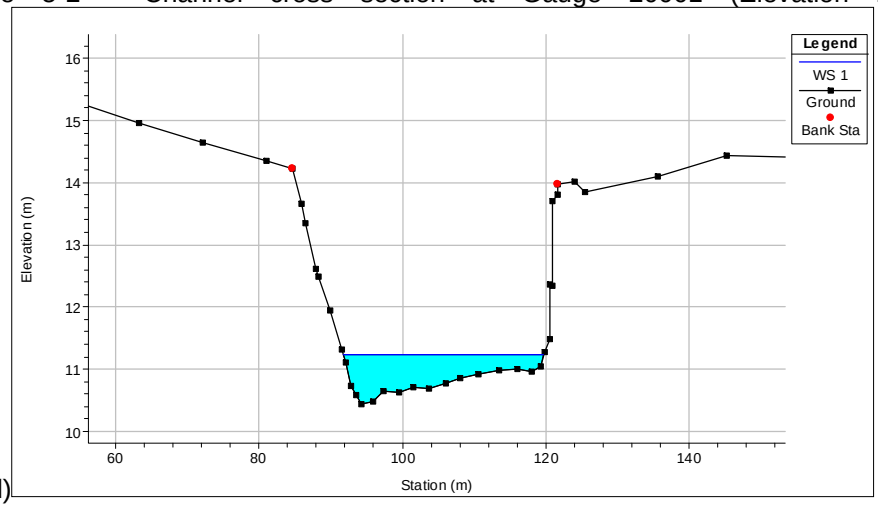
The staff gauge datum is converted to Poolbeg by the OPW, and has been further converted to Malin Head for the purposes of this study. The OPW report a zero gauge datum of 0m currently corresponds to a level at 11.14m OD (Malin); the survey recorded the gauge board datum at 11.21m OD. The OPW board datum was adopted for further analysis to maintain consistency when applying the 50 year data record at this gauge. The updated board level was tested in this assessment resulting in a minor influence of the flow predictions.

The bed level of the river at the gauge location is approximately 10.7mOD. The channel cross section is illustrated in Figure 5-2.

Table 5-1 - Changes in Gauge Zero

Start Date	Poolbeg Datum	Malin Head Datum	Comment
25/07/1960	13.893	11.183	
04/02/1972	13.877	11.167	Start of metric
28/07/1981	13.850	11.140	

Figure 5-2 - Channel cross section at Gauge 20001 (Elevation Datum Malin Head)



5.2.3 Stage – Discharge Relationship

There have been four different ratings for the Bandon gauge, all consisting of two limbs. The current rating curve has an upper limit for the rating of 5m above SG (16.21 mOD Malin); this is some 2m above top of bank.

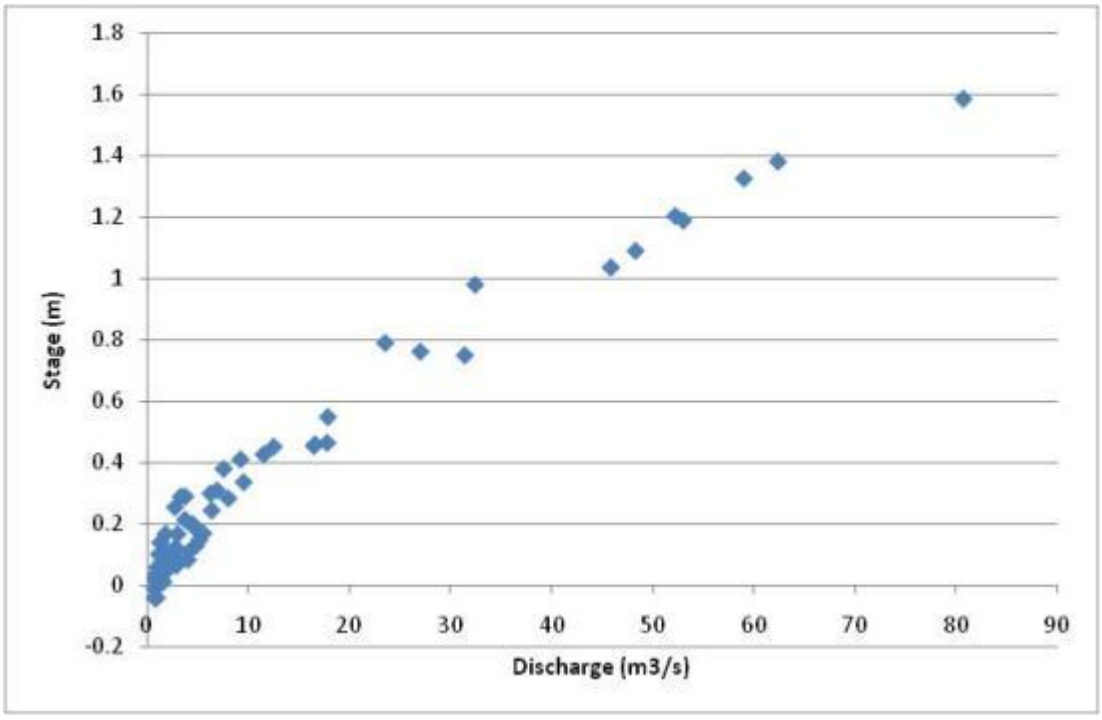
Table 5-2 - Changes in Rating Curve

Rating:	Equation No:	Equation:	UpperLimit	Valid From
1	1	40.4*(x+0.165)^2.415	1.124	01/01/1880 @ 00:00:00
1	2	33.8*(x+0.116)^1.637	5.000	
2	1	37.6*(x+0.186)^2.72	0.997	02/01/1971 @ 00:00:00
2	2	33.8*(x+0.036)^1.637	5.000	
3	1	37.6*(x+0.17)^2.72	0.403	04/02/1972 @ 15:07:00
3	2	33.8*(x+0.02)^1.637	5.000	
4	1	56*(x+0.2)^2.68	0.184	01/01/1976 @ 12:00:00
4	2	33.8*(x+0.109)^1.637	5.000	

The rating curve has not changed since 1976 although the gauge zero has changed twice in that time. This, in combination with possible geomorphological changes which are likely to have occurred since 1976, suggest here will be substantial uncertainty associated with the rating over this timeframe.

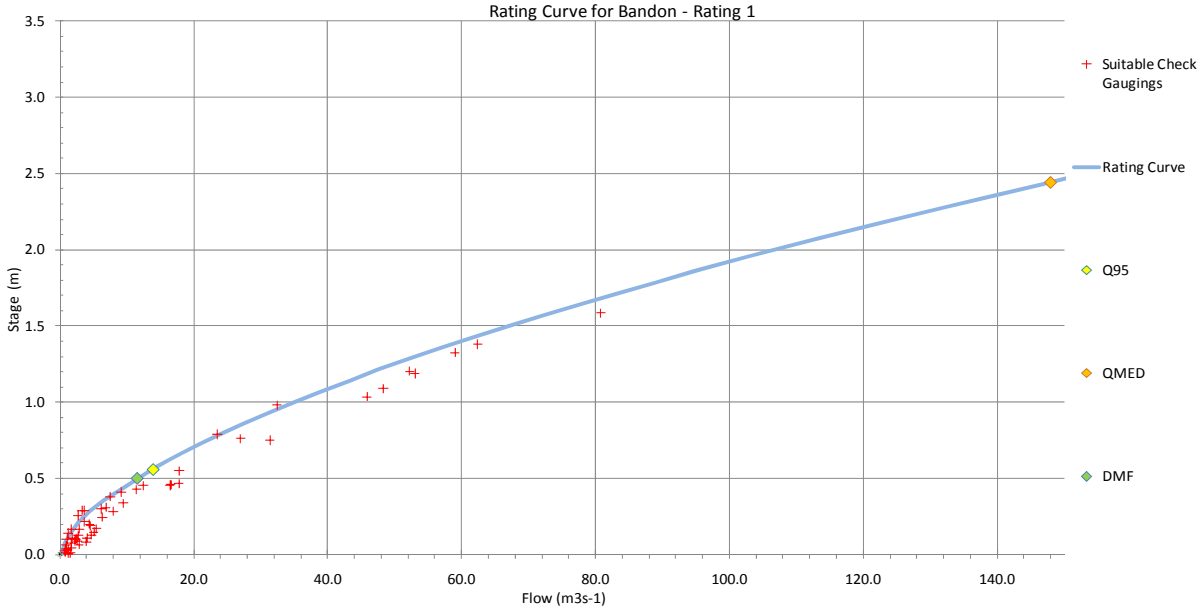
There are 59 check gaugings for the site, dating from 1964 to 1995. The maximum gauged stage is 1.585m, recorded in November 1968 (Figure 5-3).

Figure 5-3 - Check gaugings for the Bandon Gauge



A review of the check gaugings and the rating equations has been carried out using J-Racuda, JBA's custom tool for fitting and evaluating stage-discharge (see **Box 1**). The J-Racuda report is included in Appendix C. A plot showing the current rating curve (blue line) is shown in Figure 5-4.

Figure 5-4 - Rating and check gaugings



Box 1- J-Racuda

(JBA RAting CUrve Data Analysis) is a tool for fitting and evaluating stage-discharge rating curves. There are two main elements to the tool and these can be applied separately or in conjunction with each other:

1) Parameterising a stage-discharge relationship

JRacuda enables a stage-discharge relationship of the form Q= C(h-a)b to be fitted to either modelled stage-discharge data (for example outputs from an ISIS-TUFLOW model) or to check gauging information (e.g. stage-discharge pairs obtained by current metering or other spot gauging techniques). Multiple limbs may be specified and if cross-section data is available this can be plotted on the same scale as the stage-discharge data to investigate if/how inflections in the rating are related to the channel geometry). While the fitting process is automated, JRacuda allows the user to exert significant control with regard to how the rating parameterisation is carried out. It is intended that the user may wish to adjust the stage-discharge rating (e.g. by changing the number of limbs or limb break positions) after reviewing the confidence.

5.2.4 Hydraulic Modelling

Detailed hydraulic modelling has been carried out for the 20001 gauge using the ISIS-TUFLOW model of the River Bandon in Bandon. The model has been calibrated to the 2009 (out of bank) and 2011 (generally in-bank) flood events. Further details of the modelling methods and results are presented in the accompanying Hydraulics report, but the model represents the event well when considering the level record at the gauge, observed flood extents and observed flood depths.

The rating curve derived using the model is plotted in Figure 5-5, along with the OPW existing rating curve and spot check gaugings. The modelled rating shows a different curve shape to the OPW rating with slightly lower flows for medium flood events (such as 2011) but higher flows for larger flood events (such as 2009). The parameters for the rating equation are provided in Appendix C.

This rating curve suggests the 2009 event had a peak flow of around 410 m^3/s at the gauge location. The hydraulic model approximately splits this between 330 m^3/s in the channel and 80 m^3/s on the floodplain. This compares with the OPW estimate for the event of 383 m^3/s (based on the current rating equation). The 2011 event has a flow of 200 m^3/s from the OPW rating and 172 m^3/s from the model rating. The change in rating curve reduces flows in the QMED region of the curve, and reduces QMED itself for the gauge from 148 m^3/s to 122 m^3/s.

Based on the modelled ratings, the 2009 and 2011 events have growth factors of 3.36 and 1.41 above QMED.

Figure 5-5 - OPW and ISIS-TUFLOW Ratings and check gaugings for Bandon

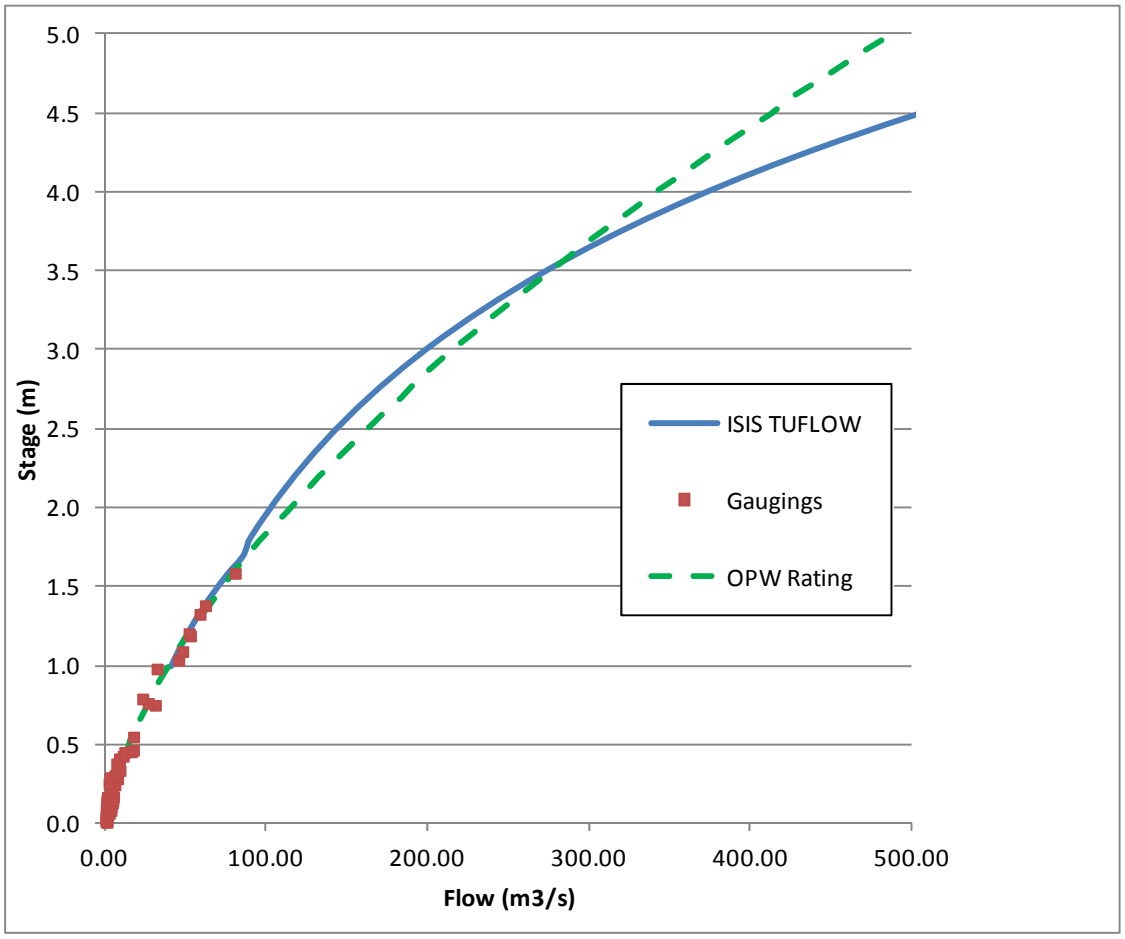
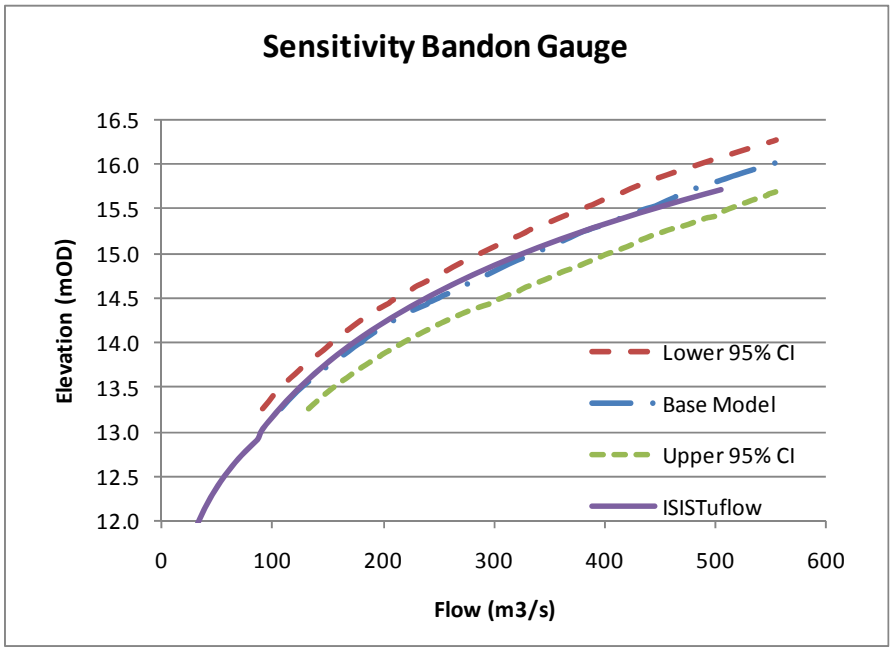


Figure 5-6 presents the updated rating (ISISTuflow) in comparison to the stage discharge relationship of the base model and its upper 95%CI and lower 95% CI These CI are based on changing the roughness of the channel and floodplain following a sensitivity analysis. Results show that a very good fit has been achieved for the Bandon Gauge for the flow range of 100m^3/s up to 500 m^3/s with some level of uncertainty with regards to the roughness and this will inform the freeboard analysis which is detailed in the hydraulic modelling report. More information on the sensitivity testing is provided in Section 6.10.

Figure 5-6 - OPW and ISIS-TUFLOW Ratings and check gaugings for Bandon



5.2.5 Summary for 20001

Detailed hydraulic modelling for gauge 20001 has produced an updated rating curve that has the effect of reducing QMED for the site from 148 m^3/s to 122 m^3/s.

The rating review has resulted in an improvement over the existing OPW rating for out of bank flows and as a results the overall, confidence in the modelled rating is high, which reflects the level of detail in the model. There remains some uncertainty with regards to QMED, the rating and the growth curve and this is presented in Section 6.10.

Given the generally high level of confidence in the rating, and the length of record at this site, the modelled rating and data for this site has been used to form the basis of the hydrological assessment for the study.

5.3 Gauge 20002 (Curranure)

5.3.1 Gauge description

The gauging station on the River Bandon at Curranure is located at grid reference W 529 571 (ING). It is approximately 3km downstream of Bandon town and 400m upstream of the confluence of the Brinny and Bandon Rivers. The gauge record began in January 1974 and digitised data is available from 1975.

The cross-section profile is open channel, with levels measured in a stilling well, as shown in Figure 5-6. The control at this station is formed by a natural rocky bed downstream of the gauge.

Figure 5-7 - Gauge at Curranure (20002) and downstream view

The OPW provided the following comments on the gauge generally, and specifically its performance during the 2009 event:

- Spot gaugings have been taken up to 102m^3/s and all these measurements are all within bank.
- Any flow estimates made above this value have been derived from an extrapolation of the within bank rating.
- The November 2009 flood reached 3.3m staff gauge (SG) at Curranure; the flow at Curranure goes out of bank at approximately 2.0m SG.
- There was significant out of bank flow at Curranure during the event.
- The flood rating at Curranure appears to be fairly consistent, with one steady relationship apparent throughout the available record. However, check gaugings are only available up to 102m^3/s and flows are extrapolate above this value.

The review of flood flow ratings undertaken as part of the FSU[12] classified this gauge as 'B'; "*flows can be determined up to Qmed with confidence. Some high flow gaugings must be around the Qmed value*".

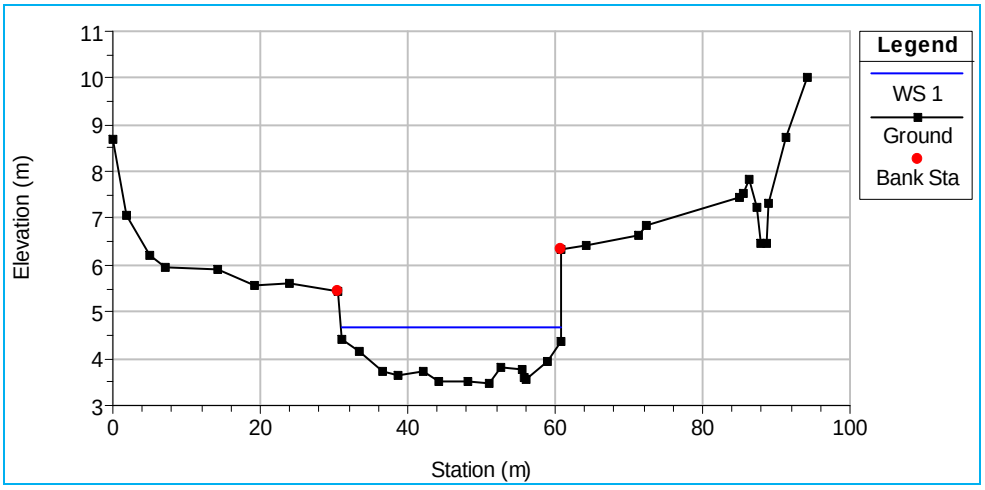
5.3.2 Gauge Datum

The height of gauge zero to national datum has remained constant since the gauge was established. As with the Bandon Gauge, the staff gauge datum is converted to Poolbeg by the OPW, and had been further converted to Malin Head for the purposes of this study. According to the OPW records, a zero gauge datum of 0m currently corresponds to a level 6.938 mOD (Poolbeg), or 4.228 mOD (Malin). The gauge zero level has been surveyed as 4.22 mOD (Malin) by Murphy's Surveys in June 2011.

The bed level of the river adjacent to the gauge is approximately 4.2mOD. The channel cross-section is illustrated in Figure 5-8.

[12] Hydro-Logic Ltd (2006) Work Package 2., Review of Flood Flow Ratings for Flood Studies Update, Flood Studies Update, Final Report

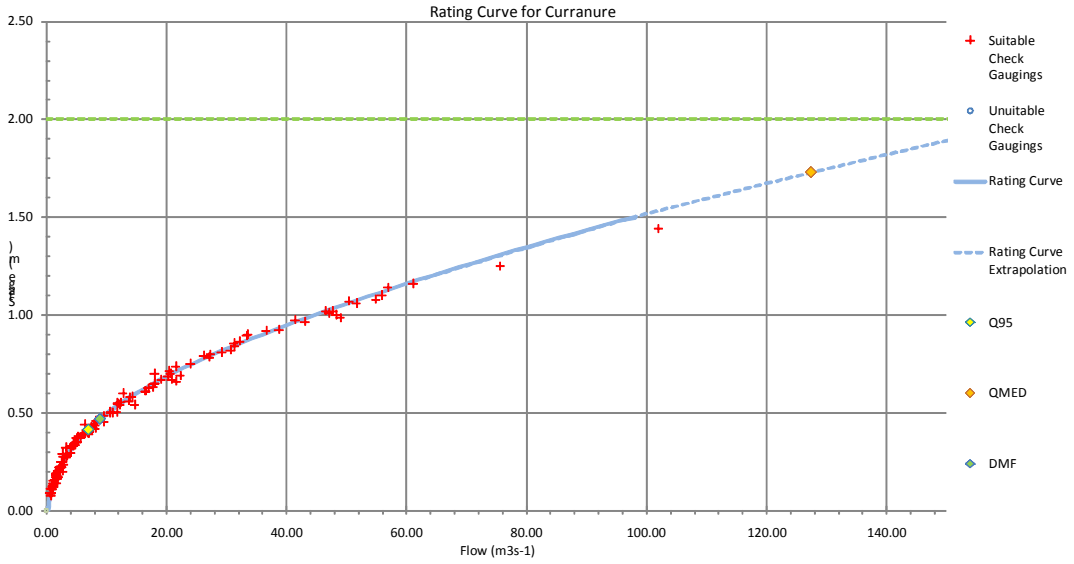
Figure 5-8 - Channel section at 20002 (Elevation Datum Malin Head)



5.3.3 Stage – discharge relationship

Figure 5-9 shows the current rating and historical check gaugings for the Curranure gauge. There are 59 gaugings for the site, dating from 1974 to 2009. The maximum gauged stage is 1.44m, as recorded in October 2009, although the comment associated with this recording states "poor site, flow all over the place"; it is unclear if difficulty in obtaining an accurate rating was also experienced during the previous gaugings, and if so, what impact on obtaining an accurate flow this is likely to have.

Figure 5-9 - Rating and check gaugings for Curranure



5.3.4 Hydraulic Modelling

Hydraulic modelling has been carried out for the 20002 gauge using the ISIS model of the River Bandon MPW. The rating curve is shown in Figure 5-9 and matches the OPW rating well over the majority of flood flows.

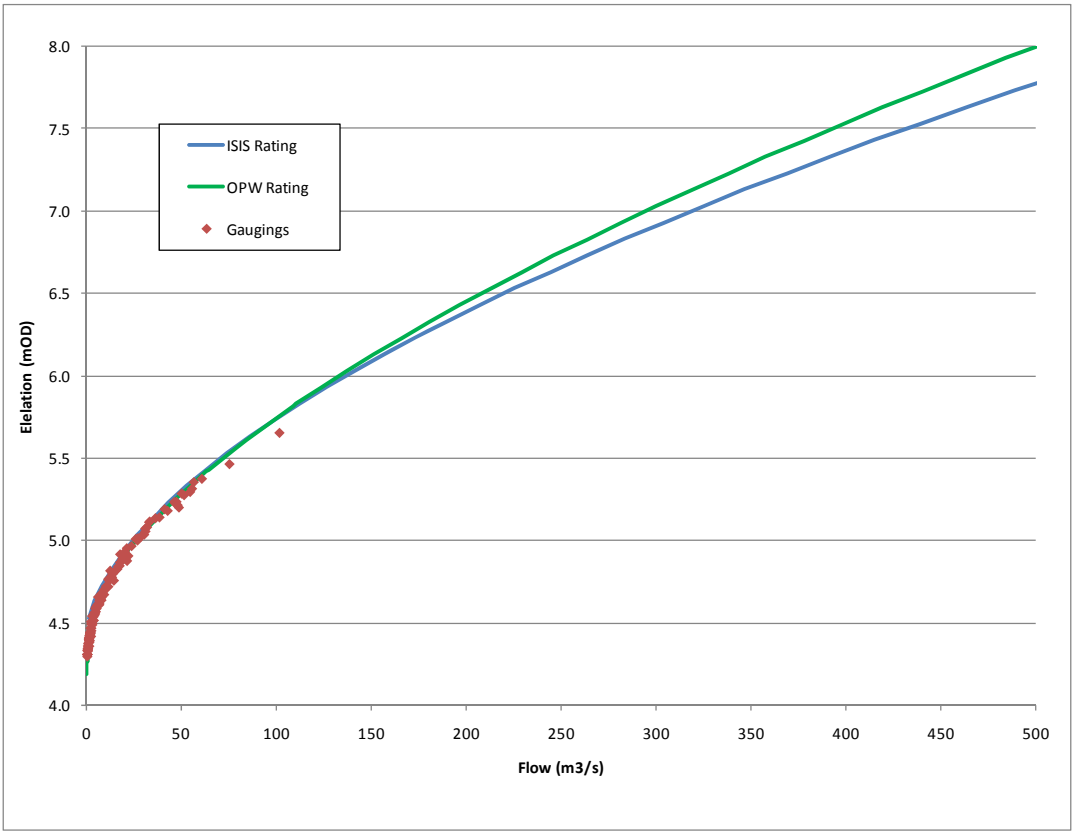
Commentary from the OPW and photographs of the site suggests natural rocky bed control is important at the gauge. During the course of the study additional cross section data was obtained along the reach of the gauge at Curranure to increase the model accuracy in the river reach.

Using the modelled rating, the 2009 peak flow for the recorded elevation of 7.46 m (mOD) is around 420 m^3/s. This corresponds closely with the peak flow estimate of around 410m^3/s

using the hydraulic model at gauge 20001 in Bandon, and compares to the OPW rating of flow of 378m^3/s.

The change in rating curve increases flows in the QMED region of the curve, and slightly increases QMED itself for the gauge from 128 m^3/s to 130 m^3/s.

Figure 5-10 - OPW and ISIS Ratings and check gaugings for Curranure



5.3.5 Summary for 20002

One-dimensional hydraulic modelling for gauge 20002 has been used to produce an updated rating curve calibrated towards the spot gaugings. The modelled rating agrees reasonably well with the OPW rating for most of the range and QMED increases from 128 m^3/s to 130 m^3/s and during large events is predicting slightly higher flows, e.g. for the 2009 event the modelled rating suggests a flow of 420m^3/s compared to 378m^3/s with the OPW rating. Additional spot gauging at high flows would be useful to improve the confidence in this rating curve.

5.4 Correspondence between 20001 and 20002

There is a discrepancy between the original OPW rated recorded flows at 20001 and 20002, with a significant number of AMAX values being higher at the upstream 20001 gauge. This manifests itself in QMED being higher at the upstream site (148 m^3/s compared to 128 m^3/s at the downstream site) for the period of overlapping record. Without extensive attenuation between the two gauges, which seems very unlikely given the relatively narrow floodplain, there would appear to be an inconsistency in the flow records associated with the ratings.

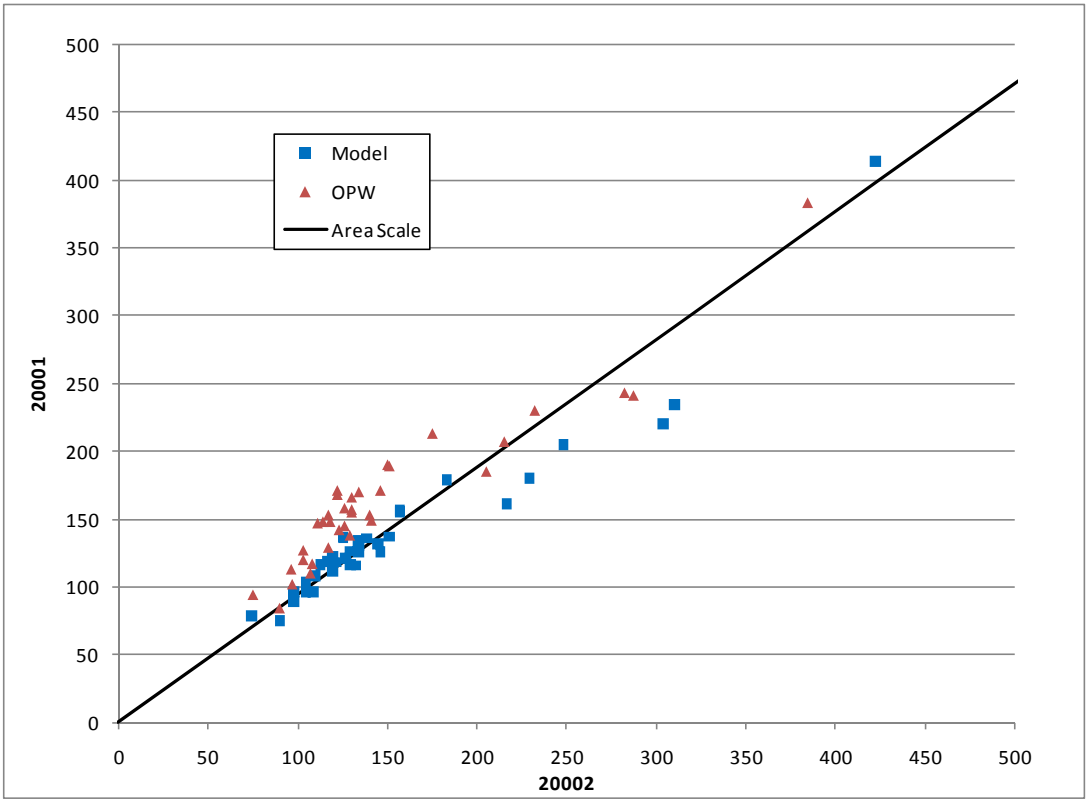
AMAX values taken from both the OPW rating, and the revised rating, for 20001 and 20002 are plotted against each other in Figure 5-10, and listed in Table 5-3. Also plotted is a line showing the expected relationship between flows at the two gauges based on the ratio of

catchment areas (406km^2 at 20001 and 431km^2 at 20002). This area-scale line gives an approximate anticipated ratio between recorded flows at the two gauges; AMAX points on the line are consistent with the relative catchment areas. The graph shows the amended rating at 20001 brings the points between 100 and 200 m^3/s much closer to the line, and therefore and more consistent with the flows recorded at 20002. At higher flows there is more scatter in the data with points falling both sides of the line.

Using the modelled rating at 20001 makes a significant difference to AMAX values, reducing the majority of them. This has the effect of reducing QMED at this site from 148 to 122 m^3/s, and bringing more consistency to QMED at both the sites, now being at 121.5 m^3/s for 20001 and 129.5 m^3/s for 20002. This is very close to ratio that would be anticipated based on relative catchment areas.

The discrepancy between the two sites was highlighted by OPW at the start of the study and this update of the rating, at 20001 in particular, now provides much greater consistency between the sites for most flood flows.

Figure 5-11 - AMAX values for gauges 20001 and 20002 using OPW and modelled rating curves plotted with a catchment area scaled linear relationship



A single site analysis has been undertaken for both gauges providing additional information on their correlation and applicability and this is presented in Section 6.3.2 and 6.3.3.

Table 5-3 - AMAX values from OPW and updated rating

Date	20001_OPW	20001_Update	20002_OPW	20002_Update
28/01/1961	105.0	92.9	No record	No record
16/03/1962	107.0	94.8	No record	No record
14/03/1963	140.0	120.7	No record	No record
10/11/1963	105.0	92.9	No record	No record
13/12/1964	195.0	171.2	No record	No record
15/02/1966	180.0	156.2	No record	No record
28/02/1967	133.0	114.5	No record	No record
24/03/1968	93.0	87.0	No record	No record
13/11/1968	90.6	84.4	No record	No record
01/02/1970	69.0	63.1	No record	No record
24/11/1970	134.0	115.2	No record	No record
01/02/1972	86.5	87.0	No record	No record
21/01/1975	117.0	108.5	108.0	109.7
23/10/1975	241.0	234.6	287.0	310.3
04/02/1977	110.0	96.7	107.0	108.4
31/10/1977	153.0	131.6	140.0	144.5
07/12/1978	185.0	161.4	205.0	216.5
27/12/1979	129.0	111.4	117.0	119.5
03/11/1980	142.0	121.6	123.0	126.7
21/02/1982	207.0	180.3	215.0	229.3
18/10/1982	102.0	89.2	96.9	97.7
13/01/1984	113.0	96.7	96.3	97.7
28/11/1984	84.4	75.3	89.8	90.0
10/08/1986	230.0	205.1	232.0	248.1
19/11/1986	155.0	130.8	130.0	134.0
13/01/1988	149.0	125.7	141.0	146.1
22/10/1988	243.0	220.1	282.0	304.1
17/12/1989	138.0	116.0	129.0	132.5
02/01/1991	171.0	137.0	146.0	150.7
25/11/1991	120.0	96.7	103.0	104.3
19/09/1993	94.2	78.5	75.0	74.3
23/02/1994	158.0	126.5	126.0	129.6
28/01/1995	148.0	118.4	118.0	120.9
13/03/1996	157.0	125.7	130.0	134.0
13/10/1996	153.0	122.4	117.0	119.5
18/11/1997	171.0	137.0	122.0	125.2
30/12/1998	170.0	136.1	134.0	138.5
21/12/1999	147.0	116.8	111.0	112.5
04/12/2001	148.0	119.1	114.0	116.7
27/11/2002	127.0	103.5	103.0	104.3

Date	20001_OPW	20001_Update	20002_OPW	20002_Update
03/02/2004	190.0	156.2	150.0	157.0
08/01/2005	213.0	179.1	175.0	183.2
22/09/2006	145.0	116.8	126.0	129.6
03/12/2006	189.0	155.2	151.0	157.0
10/01/2008	166.0	134.3	130.0	134.0
24/10/2008	168.0	136.1	122.0	125.2
19/11/2009	383.0	413.7	384.0	422.5

6. Estimation of Design Flood Flows

6.1 Overview

The UK Natural Environmental Research Council carried out a comprehensive flood study across a large number of catchments throughout Britain and Ireland. This investigation involved extensive data analysis and resulted in the publication of the Flood Studies Report (FSR)[13] which has been widely used for design flow estimation in Ireland and the UK. Since its publication in 1975, significant advancement has been gained in analytical techniques and many more years of data have become available.

The Irish Flood Policy Review Group judged that a programme of study to develop new methods, and following similar principles to the Flood Estimation Handbook (FEH)[14], will significantly improve the quality and facility of flood estimation for flood risk management in Ireland (OPW, 2004)[15]. This programme of study, the Flood Studies Update (FSU) consists of a number of Work Packages containing extensive research ranging from analysis of meteorological data to flood attenuation analysis and flood estimation for urbanised catchments. The work packages most relevant to this study are the Index Flood Estimation (FSU - WP2.3)[16] and Flood Frequency Analysis (FSU - WP2.2)[17], which are described in the following sections.

The Bandon Flood Relief Scheme primarily applies the FSU techniques, although the traditional FSR methodologies are provided as alternative methods for comparison.

6.2 FSU - Index Flood Estimation (WP 2.3)

At ungauged sites, the value of Qmed can be obtained from catchment descriptor data through the application of a regression model. As part of the FSU, a multivariate regression equation was developed on the basis of data from 199 gauged catchments, linking QMED to a set of catchment descriptors.

$$QMED_{rural}=1.237x10^{-5}AREA^{0.937}BFIsoils^{-0.922}SAAR^{1.306}FARL^{2.21}DRAIND^{0.341}xS1085^{0.185}(1+ARTDRAIN2)^{0.408}$$

Where: AREA is the catchment area (km^2).
BFIsoils is the base flow index derived from soils data
SAAR is long-term mean annual rainfall amount in mm
FARL is the flood attenuation by reservoir and lake
DRAIND is the drainage density
S1085 is the slope of the main channel between 10% and 85% of its length measured from the catchment outlet (m/km).
ARTDRAIN2 is the percentage of the catchment river network included in the Drainage Schemes
The Factorial Standard Error (FSE) of $QMED_{rural}$ in the above equation is 1.36.

The QMED estimate is multiplied by a growth factor derived either from the national, regional or pooled growth curve to arrive at the T – year flood estimate.

Table 6-1 provides flow estimates for Qmed rural and QMED with urban adjustment, as derived from the FSU catchment characteristic method. The results reflect the rural nature of the catchment, and demonstrate the small influence of urbanisation on QMED.

[13] The Flood Studies Report (1975) Natural Environment Research Council
[14] The Flood Estimation Handbook (1999) Institute of Hydrology
[15] OPW 2004. Report of the Flood Policy Review Group. Office of Public Works, Dublin, 235pp.
[16] Flood Studies Update Programme Work -Package WP-2.3 "Index Flood Estimate", Final Report NUI Galway, OPW 2009
[17] Flood Studies Update Programme Work -Package WP-2.3 "Index Flood Estimate", Final Report NUI Galway, OPW 2009

Table 6-1 - Qmed at Bandon and Curranure - FSU Statistical

	HEP 04 (Bandon)	HEP 08 (Curranure)
Qmed rural	140.9	149.5
Qmed urban	142.6	151.3

The FSU catchment characteristics for each HEP are given in Table 6-2.

Table 6-2 - Catchment characteristics

Parameter	HEP01	HEP02	HEP03	HEP04	HEP05	HEP06	HEP07	HEP08	HEP09	HEP10	HEP11	HEP14	HEP15	HEP16	HEP17
DTM_AREA	373.0	378.8	20.6	402.1	17.6	3.3	11.1	423.8	81.8	513.3	5.6	11.0	6.1	88.6	3.8
MSL	49.00	52.64	7.81	53.63	6.21	2.00	4.88	58.38	14.25	59.67	2.67	7.19	3.49	16.53	4.02
NETLEN	455.17	461.21	18.76	482.27	15.57	2.00	11.58	506.20	68.62	583.59	5.38	13.68	6.20	76.11	4.28
STMFRQ	616.00	620.00	19.00	641.00	17.00	1.00	15.00	663.00	45.00	717.00	5.00	13.00	5.00	53.00	3.00
DRAIND	1.22	1.22	0.91	1.20	0.89	0.60	1.05	1.19	0.84	1.14	0.95	1.24	1.02	0.86	1.13
S1085	2.15	2.10	16.95	2.14	19.31	13.55	22.29	2.12	7.94	2.07	30.11	13.02	24.56	6.84	13.55
TAYSLO	0.36	0.36	13.69	0.35	17.38	0.94	21.03	0.34	1.31	0.33	2.15	10.12	22.54	1.43	15.25
ARTDRAIN2	0.65	0.64	0.00	0.61	0.00	0.00	0.00	0.58	0.00	0.50	0.00	0.00	0.00	0.00	0.00
ARTDR_LEN	2.911	2.911	0	2.911	0	0	0	2.911	0	2.911	0	0	0	0	0
FARL	0.99	0.99	1.00	0.99	1.00	1.00	1.00	0.99	1.00	0.99	1.00	1.00	1.00	1.00	1.00
ALTBAR	129.4	128.4	100.3	126.6	106.4	74	125.2	123.9	113	121.1	74	92.7	71	108.7	65.4
ALT_MIN	19.1	9	9.40	9.00	27.10	35.30	42.10	0.80	14.10	0.00	13.30	9.10	0.00	0.80	5.10
ALT_MAX	543.70	543.70	201.30	543.70	201.30	154.90	201.30	543.70	219.40	543.70	121.70	160.30	121.70	219.40	123.80
SAAR	1719.58	1713.57	1307.09	1689.94	1310.9	1321.8	1313.34	1668.78	1264.33	1597.79	1224.08	1271.09	1226.37	1261.53	1296.8
SAAPE	516.94	517.06	525.53	517.56	525.51	525.08	525.92	517.89	518.96	518.17	527.43	522.19	527.42	519.43	525.26
FORMWET	0.67	0.67	0.66	0.67	0.66	0.66	0.66	0.67	0.66	0.67	0.66	0.66	0.66	0.66	0.66
URBEXT	0.33	0.38	4.35	0.78	1.32	0	0	0.81	0	0.67	0	0.79	3.54	0	0
PEAT	8.98	8.84	0	8.33	0	0	0	7.9	0	6.52	0	0	0	0	0
ALLUV	4.73	4.9	0	4.62	0	0	0	4.51	0.64	3.9	0	0.01	0.07	0.84	0.08
FOREST	11.99	12.09	4.64	11.63	5.24	14.22	3.95	11.22	4.41	10.15	0.25	1.58	0.23	4.7	1.35
ARTDRAIN	0.05	0.05	0	0.05	0	0	0	0.05	0	0.04	0	0	0	0	0
PASTURE	78.04	78.01	91.43	78.6	93.73	85.97	96.69	79.53	95.98	82.31	100	99.21	96.46	95.85	98.96
FAI_PROP	0.1024	0.1026	0.063	0.1004	0.0635	0.0751	0.0624	0.0988	0.0857	0.0961	0.0338	0.0607	0.0409	0.0828	0.089
BFISOILS	0.552	0.552	0.697	0.547	0.693	0.694	0.691	0.526	0.694	0.583	0.693	0.695	0.695	0.694	0.692
LNRESIDUAL	0.208	0.239	0.242	0.247	0.229	0.217	0.220	0.288	0.283	0.301	0.320	0.252	0.311	0.289	0.273
URBAN	0.20	0.23	2.21	0.43	0.70	0.00	0.00	0.44	0.00	0.37	0.00	0.43	1.81	0.00	0.00
Tp_0_	6.42	6.30	0.28	4.54	1.05	2.90	3.03	4.57	5.56	5.29	2.48	1.83	0.29	6.05	3.44
Tp_adjuste	6.63	6.52	0.28	4.69	1.05	2.90	3.03	4.71	5.56	5.42	2.48	1.83	0.29	6.05	3.44

6.3 FSU - Flood Frequency Analysis (WP 2.2)

WP 2.2 is based on the analysis of annual maximum flow records at approximately 200 gauging stations throughout Ireland. Guidance on flood frequency analysis is provided at both gauged and ungauged catchments and the use of growth curves based on regional pooling of data with the use of suitable 3 parameter distributions is recommended for most applications. Particular emphasis is placed on the judgement and experience of the user in order to arrive at the required design flow estimate.

The aim of flood frequency analysis is to derive a growth factor, which can be used to multiply QMED to give flows for a required design event. Flood frequency analysis for this study was undertaken using both a pooling group approach and through single site analysis. Details are presented in the following sections.

6.3.1 Pooling Group Analysis

Following the methods of the FSU WP2.2 a pooling group analysis was undertaken based on gauging station 20001.

The distance measure, dij, was applied to identify a suitable pooling group for gauging station 20001 using the catchment characteristics of AREA, SAAR and BFI. The 5T rule, where the length of the pooling group should be five times the length of the design flood, was applied and a data record of more than 500 years was considered appropriate.

Eleven stations were selected from the 88 stations that were rated as A1 and A2 as part of the FSU WP2.2. Annual Maximum data were obtained from the OPW hydrometric website. Gauging Station 20001, as the site of interest, was also included in the pooling group. Details of the pooling group are presented in Table 6-3. All members of the pooling group, with the exception of station 20001, are outside the Bandon Catchment.

Table 6-3 - Pooling group details - distance measure

Station	AM Record (years)	Start - End	AREA (km^2)	SAAR (mm)	BFI	dij
20001	50	1960-2009	402.1	1690	0.55	0.0000
16003	24	1954-1977	243.2	1192	0.55	0.0857
35001	40	1970-2009	299.5	1173	0.60	0.0876
25029	38	1972-2009	292.7	1109	0.58	0.0910
35005	62	1945-2009	639.7	1198	0.61	0.0969
14005	52	1955-2009	405.5	1015	0.50	0.1048
29011	27	1983-2009	354.1	1079	0.63	0.1084
26008	55	1955-2009	280.3	1035	0.61	0.1127
26002	58	1952-2009	641.5	1067	0.61	0.1129
30007	35	1974-2009	469.9	1115	0.65	0.1140
26019	56	1953-2009	253.0	980	0.54	0.1147
26006	57	1952-2009	184.8	1121	0.54	0.1149

The annual maximum series data of each of the pooling group stations were input into WINFAP-FEH for statistical analysis and Table 6-4 and Figure 6-1 present the results.

Table 6-4 - Pooling Group Discordancy

Station	QMED AM	L-CV	L-SKEW	Discordancy
20001	121.6	0.19	0.318	0.688
14005	50.6	0.142	0.241	0.358
35001	31.6	0.187	0.206	0.515
16003	26.7	0.031	0.176	2.626
25029	56.5	0.135	-0.032	2.794
26002	56.6	0.121	0.232	0.556
26006	26.8	0.189	0.273	0.403
26008	22.75	0.126	0.141	0.732
26019	21.2	0.137	0.219	0.829
29011	30.9	0.194	0.395	1.947
30007	63.3	0.126	0.193	0.234
35005	75.5	0.147	0.21	0.319

The H2 test shows the pooling group is acceptably homogeneous and a further review of the pooling group was not required. The results of the H2 test are presented in Table 6-5.

Table 6-5 - Heterogeneity Test - Standard Deviation of L-CV

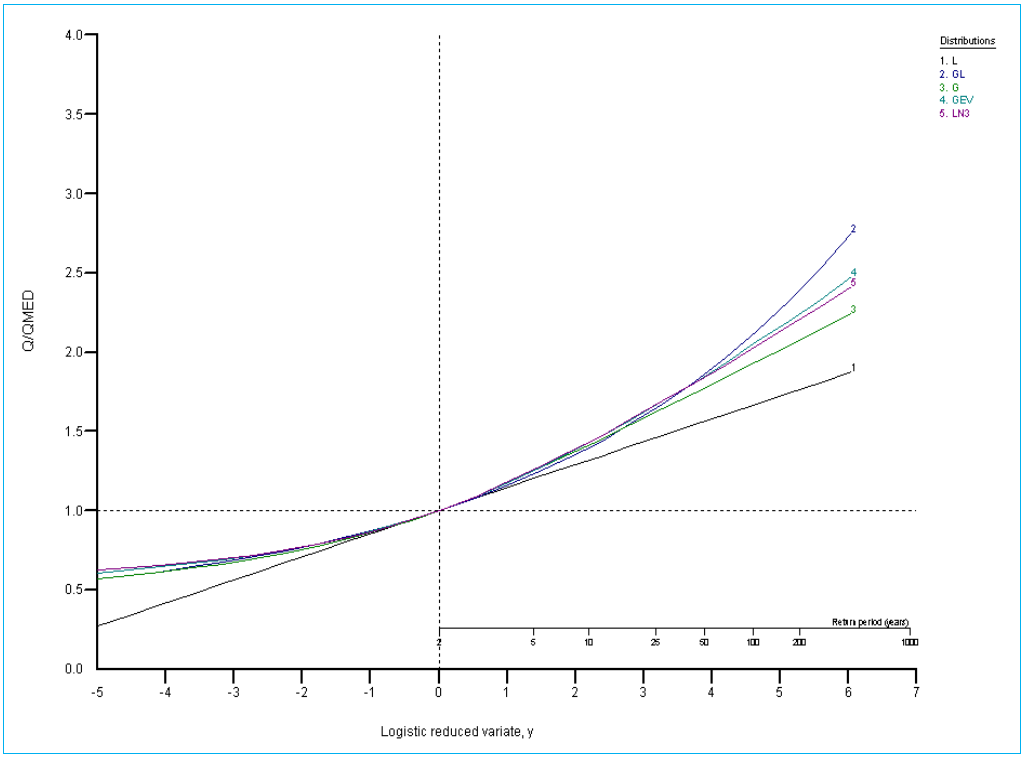
Value	Standard Deviation
Observed	0.0687
Simulated mean	0.0788
Simulated S.D.	0.0164
Standardised test Value H2	-0.4151

The goodness of fit test was undertaken and showed that the Generalised Logistic (GL) distribution provides the best fit to the pooling group data set and was also the most conservative distribution. Table 6-6 provides results from the goodness of fit test.

Table 6-6 - Goodness of Fit Test

Distribution	Value
Gen. Logistic	-0.7388
Gen. Extreme Value	-2.3653
Pearson Type III	-2.8431
Gen. Pareto	-6.1631

Figure 6-1 - Growth Curve comparison



Based on the selected pooling group, the growth factors for the various distributions were estimated, and are shown in Table 6-7, along with the Irish National growth factors. The GL was found to represent the data best, but produces a steeper growth curve when compared to the Irish National growth curve.

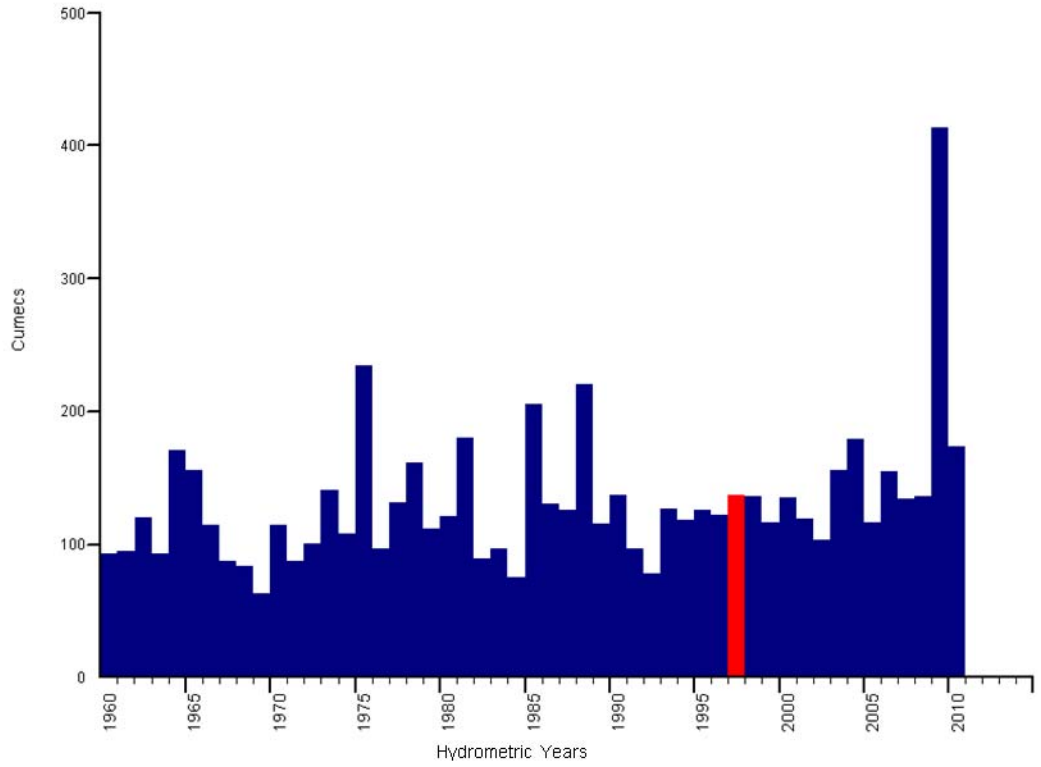
Table 6-7 - Growth Curve Comparison

Return period (years)	Logistic	Generalised Logistic	Gumbel	Generalised Extreme Value	Irish National (based on Qmed)
2	1.00	1.00	1.00	1.00	0.95
5	1.20	1.23	1.25	1.25	1.26
10	1.32	1.40	1.41	1.43	1.44
25	1.46	1.65	1.62	1.66	1.68
50	1.57	1.86	1.78	1.85	1.87
100	1.67	2.11	1.93	2.04	2.06
200	1.77	2.40	2.08	2.25	2.25
1000	2.00	3.25	2.43	2.76	2.74

6.3.2 Single Site Analysis 20001

A Single Site analysis was undertaken for gauging station 20001, which provides the most centralised location to the study area HPW and also the longest data record of the gauging stations in the Bandon River catchment. Figure 6-2 presents the annual maximum series for this station. The data presented in the table, and used in the single site analysis, are the values which have be updated following the rating review (see Section 5.2).

Figure 6-2 - Annual Maximum Series at Station 20001



The software package WINFAP-FEH was used to apply a number of typical statistical distribution methods and findings are presented in Figure 6-3 and Table 6-8.

Figure 6-3 shows that the majority of the AMAX data are well represented by both the GL distribution and the GEV distribution. It can also be seen that the most extreme event (November 2009) results in an upwards trend of the distribution curve.

Results from the Single Site analysis show that the GL distribution provides the steepest growth curve and also the best fit. The GEV distribution provides similar results for up to the 100 year return period with a slightly lower growth curve for the more extreme return periods.

Figure 6-3 - Growth Curve Fitting Single Site Analysis - 20001

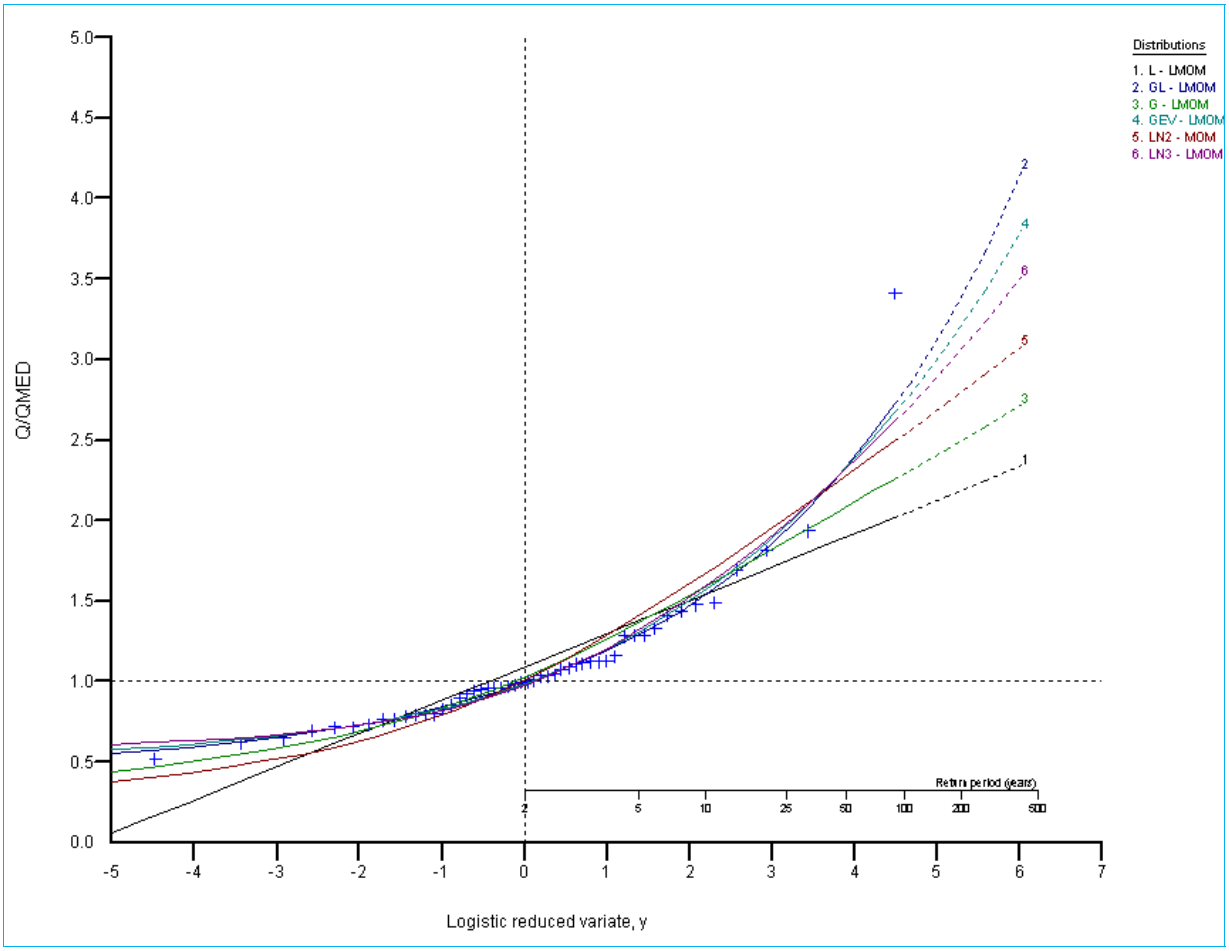


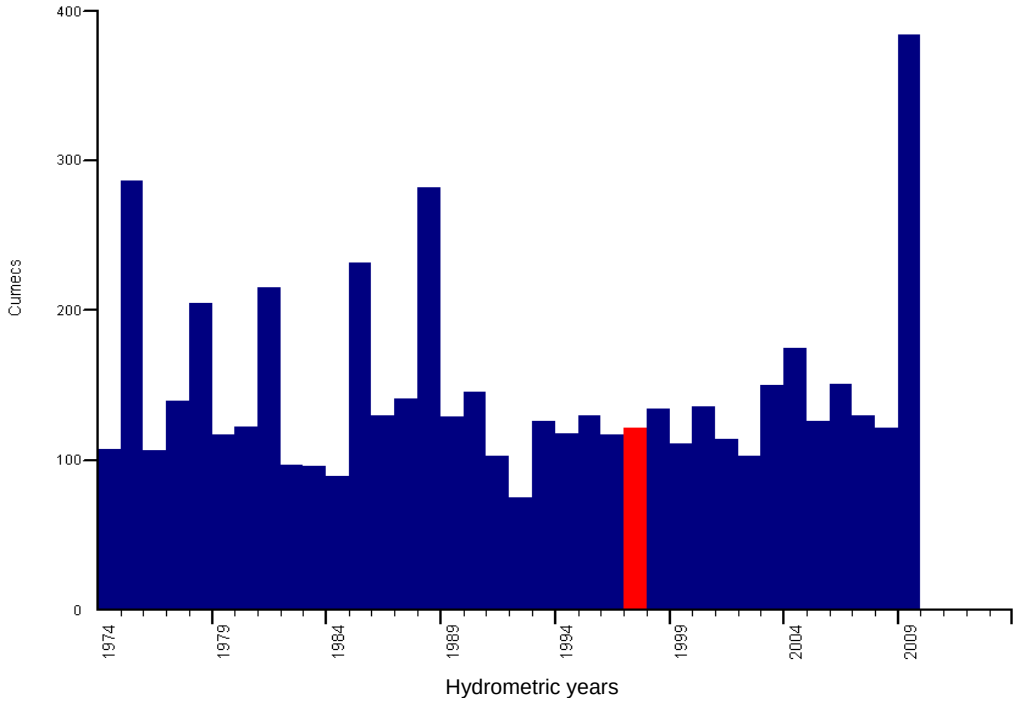
Table 6-8 - Growth Curve Fitting Single Site Analysis - 20001

Return Period	Logistic	Gen. Logistic	Gumbel	Gen. Extreme Value	Lognormal	Lognormal (3P)
	No 1	No 2	No 3	No 4	No 5	No 6
2	1.09	0.99	1.03	0.98	1.01	0.98
5	1.38	1.29	1.37	1.31	1.41	1.32
10	1.55	1.54	1.59	1.57	1.68	1.59
25	1.75	1.95	1.87	1.97	2.02	1.99
50	1.90	2.33	2.08	2.33	2.28	2.32
100*	2.04	2.80	2.29	2.74	2.54	2.68
200*	2.19	3.39	2.50	3.22	2.80	3.06
1000*	2.52	5.36	2.98	4.65	3.43	4.11
* Return Period exceeds record lengths and results should be treated with caution						

6.3.3 Single Site Analysis 20002

A Single Site analysis was undertaken for gauging station 20002, which is located approximately 5km downstream from Bandon and provides for a data record of 36 years. Figure 6-4 presents the annual maximum series for this station. The values presented inTable 6-9, and used in the analysis, are the flows derived through the rating review (see Section 5.3).

Figure 6-4 - Annual Maximum Series at Station 20002



WINFAP-FEH was used to apply a number of typical statistical distribution methods and findings are presented in Figure 6-5 and Table 6-9.

Figure 6-5 shows that there is little difference between the GEV and GL distributions, with the majority of the AMAX data being well represented by both. It is apparent that the most extreme event (November 2009) produces an upward trend in the distribution curve.

Results from the Single Site analysis show that the GEV and GL distributions provide the steepest growth curve and also the best fit. It should be noted, however that the November 2009 event is represented by both growth curves and this is unusual, as this event is generally found to be an outlier (as it was at station 20001) due to its severity.

Figure 6-5 - Growth Curve Fitting Single Site Analysis - 20002

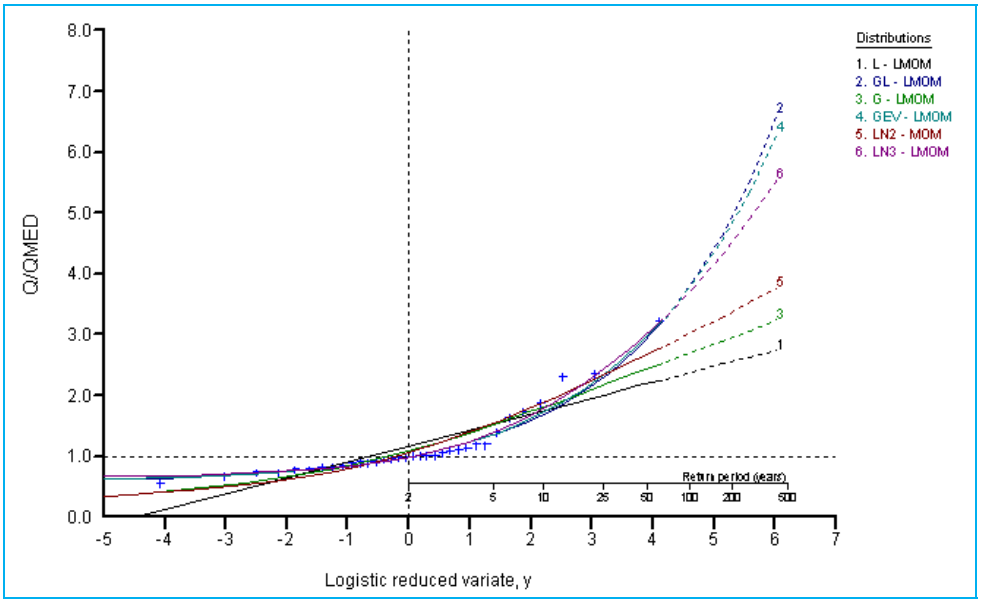


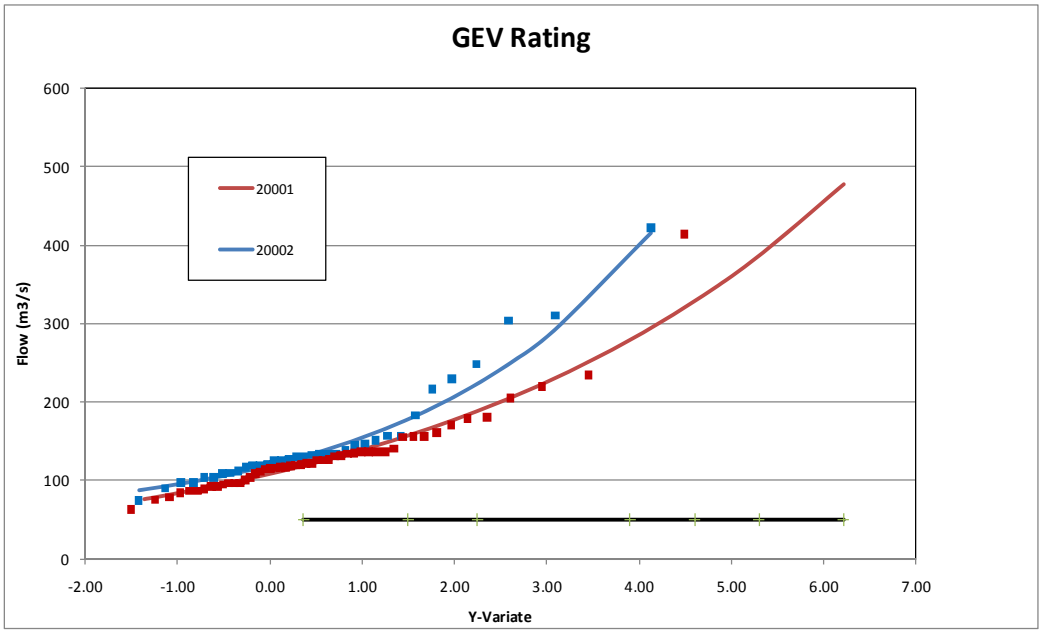
Table 6-9 - Growth Curve Fitting Single Site Analysis - 20002

Return Period	Logistic	Gen. Logistic	Gumbel	Gen. Extreme Value	Lognormal	Lognormal (3P)
	No 1	No 2	No 3	No 4	No 5	No 6
2	1.174	1	1.094	0.995	1.06	0.982
5	1.539	1.358	1.524	1.368	1.549	1.395
10	1.752	1.693	1.809	1.721	1.889	1.783
25	2.01	2.296	2.169	2.338	2.333	2.419
50	2.198	2.932	2.436	2.965	2.674	3.009
100*	2.383	3.787	2.701	3.778	3.024	3.706
200*	2.567	4.943	2.965	4.835	3.383	4.522
500*	2.809	7.121	3.314	6.737	3.877	5.807
* Return Period exceeds record lengths and results should be treated with caution						

6.3.4 Growth Curve Comparison 20001 and 20002

A comparison of the growth curves at Bandon (20001) and Curranure (20002) was undertaken. It should be noted that the majority of annual maximum flow records are extrapolated above the reliable limit of the gauging records (see Section 5) and each of the rating curves has a degree of uncertainty arising from both flow and water level recordings. Figure 6-6 shows the growth curves for both stations using the GEV distribution.

Figure 6-6 - Rating Comparison 20001 and 20002



The Curranure growth curve is steeper than the curve for Bandon and would be considered exceptionally steep (growth factor for 100 year event is 3.38). This is further supported by its fitting to the 2009 event, which would generally be considered an outlier, and would not be expected to fit the standard distributions. There are a number of reasons that could have resulted in the discrepancy between the two growth curves, such as measurement error, changes in hydromorphology, changes in vegetation, difference in record length and its effect on the statistical analysis as well as uncertainties in the hydraulic model.

Both gauging stations are located in relative close proximity (5km apart) on the Bandon River and it would be unrealistic to apply both growth curves within the study, particularly as they are so different. The Bandon gauge growth curve is considered to be the more

representative of the two, being based on a longer record, having a more detailed model to derive the rating update and being closer to the primary area of interest.

6.4 FSR - Traditional Methods

The Bandon Flood Study is a pilot project that applies the latest findings from the FSU Work Packages. As a result, it was decided to compare finding with the traditional FSR methodologies which are detailed in the following sections. Appendix A provides information on each of the input parameters and also provides the output hydrographs for each HEP from the FSR RR method.

6.4.1 FSR Six Variable Equation (1975)

The Bandon Flood Study is primarily based on the FSU methodology and the FSR flow estimation method is provided for comparison only.

The FSR six-variable catchment characteristic regression equation for Ireland to estimate the mean annual maximum flood is as follows:

$$QBAR = C\ AREA^{0.95} FS^{0.22} SOIL^{1.18} SAAR^{1.05} S1085^{0.16} (1+LAKE)^{-0.93}$$

where the multiplier C = 0.00042 for Ireland.
AREA is the catchment area (km^2).
FS (stream frequency) is the number of stream junctions per km^2 on a 1:25,000 scale map.
S1085 is the slope of the main channel between 10% and 85% of its length measured from the catchment outlet (m/km).
SAAR is long-term mean annual rainfall amount in mm
SOIL is an index of how the soil may accept infiltration and is a measure of the Winter Rainfall Acceptance Potential (WRAP). The index is based on only five classifications (very high, high, moderate, low and very low WRAP) and the mapping scale and number of categories are regarded as providing a very coarse measure of catchment runoff potential.
LAKE is an index defined as the fraction of catchment draining through lakes or reservoirs and the areas contributing to lakes whose surface area exceeds 1% of the contributing area is recorded.
The FSR equation has a standard factorial error of 1.456

Table 6-10 presents Qbar for the FSR Statistical Method derived at Bandon and Curranure.

Table 6-10 - Qbar at Bandon and Curranure - FSR Statistical

	HEP 04 (Bandon)	HEP 8 (Curranure)
Qbar	90.57	98.9

6.4.2 Rainfall Runoff (Unit Hydrograph)

The unit hydrograph method estimates the design flood hydrograph, describing the timing and magnitude of flood peak and flood volume. The method requires the catchment response characteristics, design rainstorm characteristics and runoff / loss characteristics to be input.

The instantaneous triangular unit hydrograph is defined by a time to peak, T_p, a peak flow in cumecs/100km^2, $Q_p = 220/T_p$, and a base length $T_B = 2.52T_p$. The rainstorm profile used in this analysis is the FSR 75% Winter Profile for Ireland.

The unit hydrograph describes the theoretical response of the catchment to an input of a unit depth of rainfall over a unit of time. Table 6-11 provide results from the FSR RR method at Bandon and Curranure and Appendix A provides details of the model parameters, which were estimated from catchment characteristics, as well as design flow hydrographs for each HEP.

The FSR RR method in this study used catchment descriptors. Available rainfall data was not suitable for improving the estimate, as rainfall data was only available in daily totals. This does not provide a high enough resolution to assess the time to peak flow.

Table 6-11 - Design flow estimates - FSR Rainfall Runoff

Return Period	HEP04 (Bandon)	HEP8 (Curranure)
2	150.3	152.5
5	203.8	206.3
10	233.6	236.2
50	307.9	311.1
100	343.3	346.6
200	384.0	387.5
1000	488.6	492.6

6.5 Data transfer from gauged catchments to estimate QMED at ungauged sites (Donor Catchment Analysis)

The FSU recommends that use is made of donor catchments to improve estimates of the index flood at ungauged sites. Based on the methodology of the FSU the catchment characteristics-based estimate of QMED at each subject site is scaled by the ratio of observed and estimated QMED values at the donor site, so that;

$QMED_A = QMED(estimated)_A * QMED(measured)_B/QMED(estimated)_B$

Where subscript A refers to the subject site and subscript B refers to the donor site. A donor catchment assessment was undertaken using the Bandon Gauge (20001) located downstream of Bandon Bridge, which also receives flows from the Bridewell River. Details of each hydrological flow estimation point are presented in Table 3-2. The most appropriate method for estimating QMED is the FSU Index Flood Estimation as detailed in Section 6.2. . Table 6-12 presents the estimated and adjusted QMED values.

Table 6-12 - Comparison of estimated and adjusted QMED

HEP	Estimated QMED - (FSU)	Adjusted $QMED_A$
	m^3/s	m^3/s
1	135.1	116.5
2	135.4	116.8
3	5.6	4.9
4 (Donor Site)	140.9	121.6 (Recorded)
5	5.0	4.3
6	0.9	0.7
7	3.5	3.0
8	149.5	129.0
9	16.7	14.4
10	156.7	135.2
11	1.7	1.5
14	3.2	2.8
15	1.8	1.6
16	17.6	15.2
17	1.2	1.0

It is recommended to adopt this method of data transfer from the Gauge 20001 (Bandon town gauge) to all of the HEPs in the study area for the following reasons:

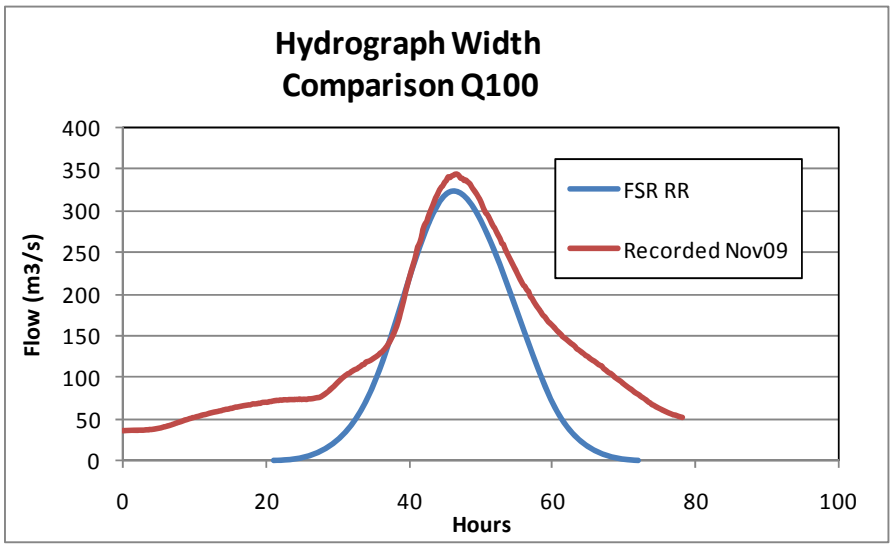
1. Bandon town gauge provides more than 50 years of data record.
2. Bandon town gauge is located at the centre of the area of interest and within the HPW model, which is modelled using the detailed 1D/2D model.
3. The rating review of the Bandon town gauge showed that overall, confidence in the modelled rating is high, which reflects the level of detail in the model.
4. All of the HEPs are located within close proximity to the Bandon town gauge.
5. The climatic conditions of all of the HEPs are similar to the Bandon town gauge.
6. The majority of the catchment characteristics are similar to the Bandon town gauge,
7. Sensitivity testing of alternative flow estimation techniques for small catchments within the HPW model showed little difference to the proposed design flows.
8. The FSU Index Flood Estimation is the most accurate catchment descriptor based flow estimation available to derive the index flood.
9. The recommended 1000 year growth factor is more conservative than the equivalent FSR national growth factor or the corresponding flows from the Rainfall Runoff method.

It should be noted that the confidence in the derived flow estimation for the Bandon River is high as outlined under point 1, 2 and 3. The confidence in the flow estimation for the tributaries is less certain due to the lack of gauging stations. Please see section 6.9 for more information.

6.6 Inflow Hydrographs

The hydrograph shape was initially derived using the unit hydrograph method as part of the FSR Rainfall Runoff approach. However, as time series data records are available for the Bandon River from gauging stations 20001 and 20002, the modelled hydrograph was compared to gauging records for the 2009 event, as presented in Figure 6-7.

Figure 6-7 - Comparison of Hydrograph Shape - 20001



The event data showed a longer time to peak and a wider hydrograph at the gauge on the Bandon River. No event data was available for the tributaries so it was decided to adopt the event hydrograph shape for the Bandon River and the modelled hydrograph shape for the tributaries.

The inflow hydrographs for the Bandon River, Bridewell River, Millstream, Brinny River and Inishannon River were input to the model at their relevant HEPs. The recorded hydrograph shape was applied to peak flows in the Bandon River, whilst the FSR Rainfall Runoff

hydrograph shape was adopted for the tributaries. Each modelling run was undertaken with a specific return period, as estimated at each HEP. This was achieved by scaling inflow hydrographs to match the relevant peak flow estimates. Additional lateral inflows were added along the Bandon River and tributaries in order to match the peak flow estimates to provide consistency between the hydrological assessment and the hydraulic analysis.

6.7 Comparison of Methods

The flow estimation methods were compared in terms of median flow estimate and the derived growth curves, as shown in Table 6-13 for 20001 and 20002.

When compared with the flow records, the FSR Catchment Characteristic method (FSR STAT) resulted in underestimation of QMED at gauging station 20001 of almost 30% and 27% at gauging station 20002. The equivalent FSU method resulted in an overestimation at gauging station 20001 and 20002 of 16% and 17%, respectively. The FSR Rainfall Runoff method was found to overestimate QMED by 24% and 20%.

Table 6-13 - Comparison of Flow Estimation Methods for Median Flood

	HEP04 (Bandon)		Difference	HEP08 (Curranure)		Difference
	(m^3/s)	Absolute	Percentage	(m^3/s)	Absolute	Percentage
Recorded	121.6	0.0	0%	129.5	0.0	0%
FSU STAT	140.9	12.7	16%	149.5	22.0	17%
FSR STAT	90.57	-35.3	-29%	98.9	-33.8	-27%
FSR RR	150.3	29.2	24%	152.5	25.0	20%

Figure 6-8 presents a comparison using the derived growth factors for the various flow estimation methods and covering a range of return periods. The annual maximum flow values at the Donor Site (Gauging Station 20001, HEP04) are included to provide an indication of the goodness of fit for each method.

It can be seen that growth curves derived from the pooled analysis and single site analysis are significantly steeper than the Irish National growth curve or the FSR RR derived growth curve.

Findings show that the FSR RR method results in consistently higher growth factors for the lower return periods, such as the 2, 5, 10 and 25 year return period.

The GL distribution of the pooled analysis results in a slightly steeper growth curve than the Irish National growth curve, with a growth factor of 2.11 for the 100 year return period. The GL distribution results in an upwards trend for the higher return periods with similar results for the lower return period flows in comparison to the GEV distribution.

The GEV and GL distribution derived from the single site analysis at gauging station 20001 show a similar growth curve for up to 100 year return period. The GL distribution also provides the most conservative design flow estimation for the 1000 year return period at Bandon.

Figure 6-8 - Comparison of Growth Curves using FSU and FSR methods

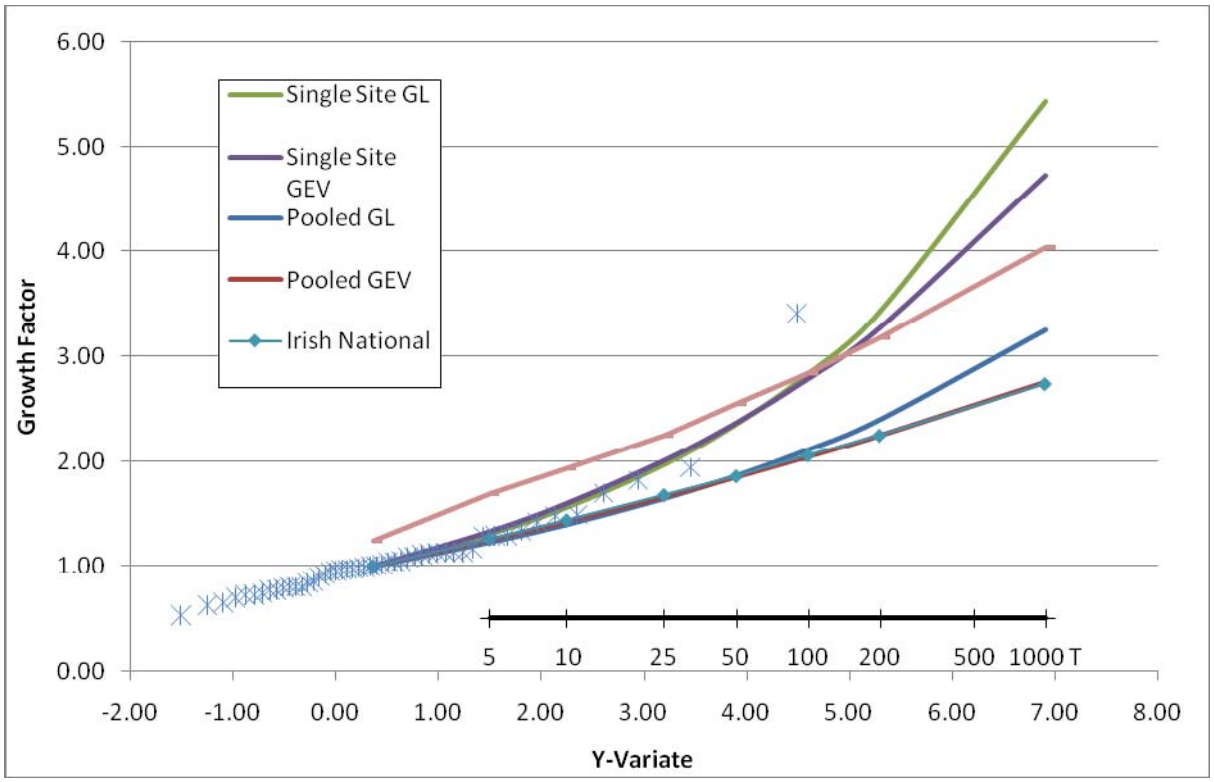


Table 6-14 - Comparison of Growth Curves using FSU and FSR methods.

Return Period	Pooled		Single Site		FSR RR	Irish National
Years	GL	GEV	GL	GEV		
2	1.00	1.00	1.00	1.00	1.24	1.00
5	1.23	1.25	1.31	1.33	1.68	1.26
10	1.40	1.43	1.56	1.60	1.93	1.44
25	1.65	1.66	1.97	2.01	2.25	1.68
50	1.86	1.85	2.36	2.37	2.54	1.86
100	2.11	2.04	2.84	2.79	2.84	2.06
200	2.40	2.25	3.43	3.28	3.17	2.25
1000	3.25	2.76	5.43	4.73	4.04	2.74

6.8 Final Choice of Scheme Design Flows

All of the different flow estimation methods are valid ways of deriving design flow estimates.

Following the gauging station review, QMED is estimated from the gauged record as 122m^3/s for Bandon town gauge, and 130m^3/s for the Curranure gauge. Given the generally high level of confidence in the rating at the Bandon town gauge, data for this site has been used to form the basis of the hydrological assessment for the study and has been applied as donor data for the hydrological flow estimation points.

The FSR Statistical method was found to underestimate QMED when compared to recorded data, whereas the FSR Rainfall Runoff method and the FSU Statistical Method were found to overestimate QMED. The most extreme event, of November 2009 was found to significantly influence the growth curve characteristics, particularly of the single site analysis, which results in an upward trend towards the higher return period.

The pooling group analysis produces a more moderate growth curve, due to the spatial distribution and length of the combined data record with less influence of the November 2009 event. However, results suggest that the return period of the three most extreme events, as recorded at gauging station 20001, would be overestimated by the pooling group. The November 2009 event would result in a return period in excess of 1000 years, the second highest event would result in a return period of more than 50 years and the third highest event would be estimated around a 50 year return period. This would be significantly different to the findings of the Gringorten analysis, and previous studies.

As a result, it is recommended to adopt the GEV distribution that is derived from the single site analysis at Gauging Station 20001 (HEP04). Table 6-15 presents the final design flows.

Table 6-15 - Final Scheme Design Flows - Based on HEP04 as a Donor Site

Return Period	Growth Factor (GEV)**	HEP01	HEP02	HEP03	HEP04	HEP05	HEP06	HEP07	HEP08	HEP09	HEP10	HEP11	HEP14	HEP15	HEP16	HEP17
2	1.00	116	117	4.9	122	4.3	0.7	3.0	129	14.4	135	1.5	2.8	1.6	15.2	1.0
5	1.33	155	155	6.5	162	5.7	1.0	4.0	172	19.1	180	2.0	3.7	2.1	20.2	1.4
10	1.60	186	187	7.8	194	6.9	1.2	4.9	206	23.0	216	2.4	4.4	2.5	24.3	1.6
50	2.37	276	277	11.5	288	10.2	1.8	7.2	306	34.1	320	3.6	6.6	3.8	35.9	2.4
100*	2.79	325	326	13.6	339	12.0	2.1	8.5	360	40.2	377	4.2	7.7	4.4	42.3	2.9
200*	3.28	382	383	16.0	399	14.1	2.4	10.0	423	47.2	443	4.9	9.1	5.2	49.7	3.4
1000*	4.73	551	553	23.0	575	20.3	3.5	14.4	610	68.1	639	7.1	13.1	7.5	71.7	4.8

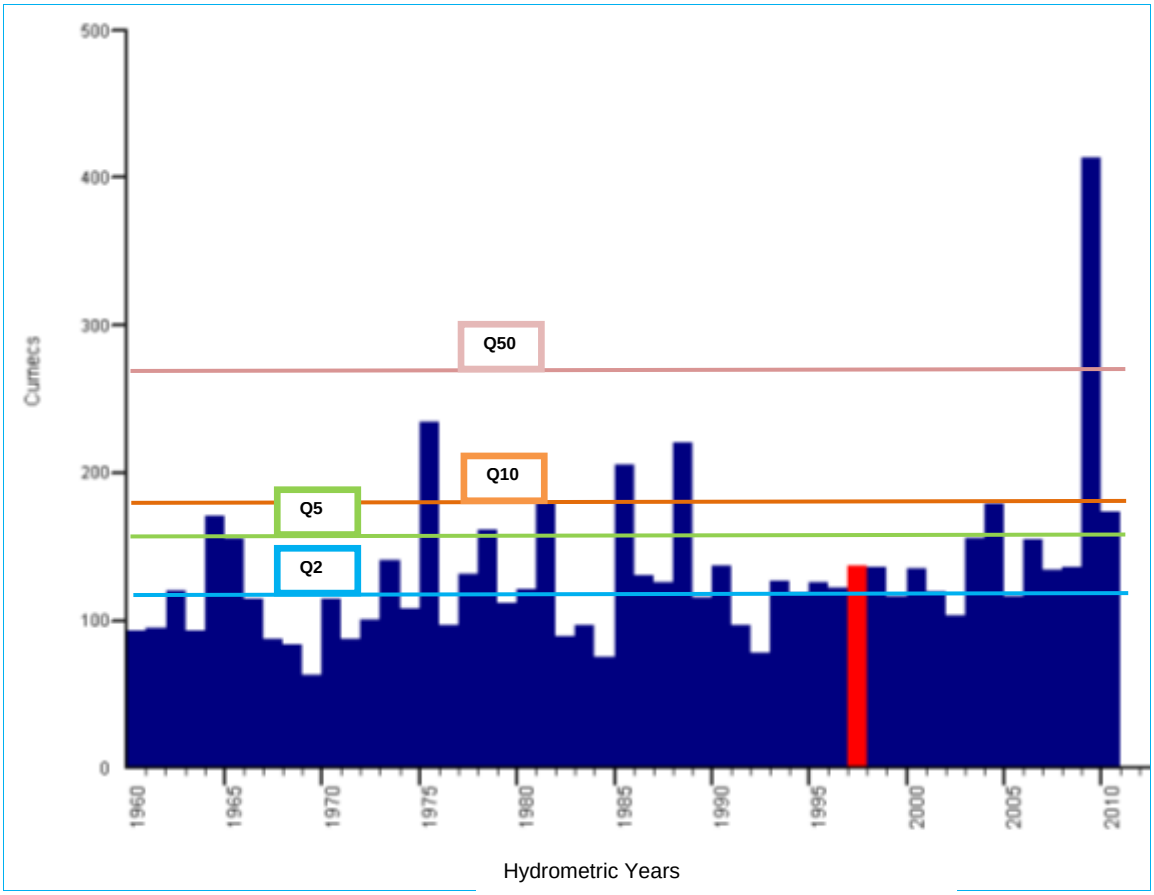
* Return Period exceeds record lengths and data should be treated with caution

The flood event of November 2009 is estimated at 410m^3/s, which, based on the design flow is estimated to be around the 1 in 200 year return period event (HEP04). This is in good agreement with the results of the Gringorten analysis of 160 year return period (see Section 2.3.5).

The recommended design flows were compared to the annual maximum flow series at gauging station 20001. This comparison is a simple test showing whether the numbers of exceedances for the relevant return periods are plausible, i.e. for the 50 years of data record the 5 year return period is expected to be exceeded approximately 10 times.

Figure 6-9 presents the annual maximum flow series in comparison to the recommended design flows. Findings show that the design flows of the 2, 5 and 10 year return period would have been exceeded 26, 9 and 4 times respectively. This comparison provides a good estimate for the expected exceedance intervals of 26, 10 and 5 times for the 2, 5 and 10 year return period, respectively.

Figure 6-9 - Comparison of Annual Maximum Data with Design Flow Estimate - GS 20001



6.9 Alternative Flow Estimation Methods for Small Catchments

The Bridewell River and Milllstream form part of the HPW model and their catchment areas are significantly smaller and steeper than the Bandon River Catchment, upon which the design flow estimation is based. The design flows, as derived based on the FSU methods described above, were compared to a number of alternative flow estimation methods. Methods which are known to be suitable for small catchments were applied to five of the hydrological estimation points (as listed in Table 6-16). The methods applied were the Rational Method, the FSR 6 Variable Equation, Poots Cochrane and the Institute of Hydrology Report No. 124, as described briefly in the following sections. For details on the FSR 6 Variable Equation please refer to section 6.4.

Table 6-16 - Small Catchment HEPs

HEP	Coordinates		Watercourse	Description
3	149296	55074	Bridewell	Downstream modelled limit
5	148160	53943	Bridewell	Downstream of junction with unnamed tributary
6	147206	53686	Unnamed tributary of the Bridewell	Upstream modelled limit
7	147568	53015	Bridewell	Upstream modelled limit
14	150296	55349	Mill Stream	Downstream end of watercourse

Rational Method

$Q_T = 0.278\ C_P \times C_{RT} \times i_T \times A$

Where:
C_P is the peaking factor taken as 1.3
C_{RT} is the runoff coefficient for Return Period T years
i_T is the average rainfall intensity for design duration of T_C hours in return period years.
TC is the time of concentration defined as the travel time from the furthest point on the catchment outlet (hrs)
A is the catchment Area

Poots Cochrane

$$Q_{bar} = 0.0136 \times F_N \times A^{0.866} \times RSMD^{1.413} \times SOIL^{1.521}$$

Where:
A is the catchment Area
RSMD is the residual soil moisture deficit
SOIL is the soil index
F_N is 2.7 for 95% confidence limit.[18]

Institute of Hydrology Report No. 124

$$Q_{bar} = 0.00108 \times A^{0.89} \times SAAR^{1.17} \times SOIL^{2.17}$$

Where:
A is the catchment area
SAAR is the standard annual rainfall
SOIL is the soil index

Table 6-17 presents the input parameters to the alternative flow estimation methods and Table 6-18 presents the flow estimations for each method, including the data transfer method used under the FSU. The flood frequency curves for HEP03 and HEP14, which are located at the downstream end off the Bridewell River and Millstream, respectively are shown in Figure 6-10 and Figure 6-11. Results for the Rational Method are not displayed as these are overestimating flows and are not appropriate and would also make a comparison of the remaining flows difficult. Section 6.9.1 presents a discussion and recommendation on findings of this assessment.

Table 6-17 - Input parameters

	Parameter	HEP03	HEP05	HEP06	HEP07	HEP14
Rational Method	Runoff Coefficient (based on FSSR 16)	0.375	0.375	0.372	0.372	0.38
	Storm Duration (hours)	3.37	3.26	2.897	3.032	3.96
	Time of Concentration (hours)	3.37	3.26	2.897	3.032	3.96
	Rainfall Intensity T2 (mm/hr)	9.82	5.34	11.45	10.98	4.82
	Q2 (m^3/s)	21.11	9.78	3.92	12.56	5.63
IH 124	SOIL	0.3	0.3	0.3	0.3	0.3
	AREA (km^2)	20.62	17.56	3.31	11.06	11.05
	SAAR (mm)	1307	1310	1322	1313	1271
	Qbar (m^3/s)	4.91	4.42	0.98	2.84	2.73
Poots Cochrane	AREA (km^2)	20.62	17.56	3.31	11.06	11.05
	RSMD	50.79	44.38	46.30	44.49	45.27
	SOIL	0.3	0.3	0.3	0.3	0.3
	FN	1	1	1	1	1
	Qbar (m^3/s)	7.30	5.25	1.31	3.53	3.61

[18] Donaill, C. (2001). Culvert Hydraulics and Section 50 Consent. National Hydrology Seminar, Ireland

Table 6-18 - Comparison of flow estimations for the tributaries HPW, HEP3, 5 & 6

Return Period	HEP03 (m^3/s)					HEP05 (m^3/s)					HEP06 (m^3/s)				
	Data Transfer	FSR 6 Var	IH124	Poots Cochrane	Rational Method	Data Transfer	FSR 6 Var	IH124	Poots Cochrane	Rational Method	Data Transfer	FSR 6 Var	IH124	Poots Cochrane	Rational Method
2	4.9	5.1	4.9	7.3	21.1	4.3	3.7	4.4	5.3	9.8	0.7	0.7	1.0	1.3	3.9
5	6.5	6.5	6.2	9.2	29.5	5.7	4.7	5.6	6.6	12.7	1.0	0.8	1.2	1.7	5.5
10	7.8	7.4	7.1	10.6	34.2	6.9	5.4	6.4	7.6	15.1	1.2	0.9	1.4	1.9	6.4
50	11.5	9.6	9.2	13.7	45.3	10.2	7.0	8.3	9.8	22.0	1.8	1.2	1.8	2.5	8.4
100	13.6	10.5	10.1	15.1	50.6	12.0	7.7	9.1	10.8	25.8	2.1	1.3	2.0	2.7	9.4
200	16.0	11.6	11.1	16.5	56.7	14.1	8.5	10.0	11.9	30.3	2.4	1.5	2.2	3.0	10.5
1000	23.0	14.0	13.5	20.1	71.8	20.3	10.3	12.1	14.4	43.9	3.5	1.8	2.7	3.6	13.3

Table 6-19 - Comparison of flow estimations for the tributaries HPW, HEP7 & 14

Return Period	HEP07 (m3/s)					HEP14 (m3/s)				
	Data Transfer	FSR 6 Var	IH124	Poots Cochrane	Rational Method	Data Transfer	FSR 6 Var	IH124	Poots Cochrane	Rational Method
2	3.0	2.7	2.8	3.5	12.6	2.8	2.4	2.7	3.6	5.6
5	4.0	3.4	3.6	4.5	17.6	3.7	3.1	3.4	4.6	7.3
10	4.9	3.9	4.1	5.1	20.4	4.4	3.5	3.9	5.2	8.6
50	7.2	5.0	5.3	6.6	26.9	6.6	4.6	5.1	6.8	12.5
100	8.5	5.5	5.9	7.3	30.1	7.7	5.0	5.6	7.5	14.6
200	10.0	6.0	6.4	8.0	33.7	9.1	5.5	6.2	8.2	17.1
1000	14.4	7.3	7.8	9.7	42.7	13.1	6.7	7.5	9.9	24.6

Figure 6-10 - Comparison of design flow estimations for HEP03

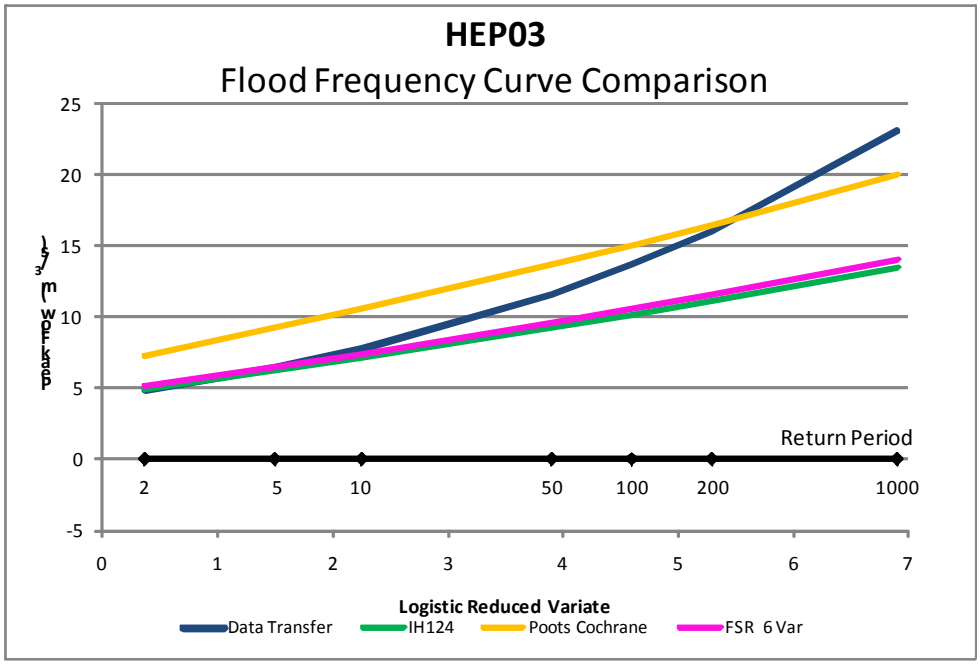
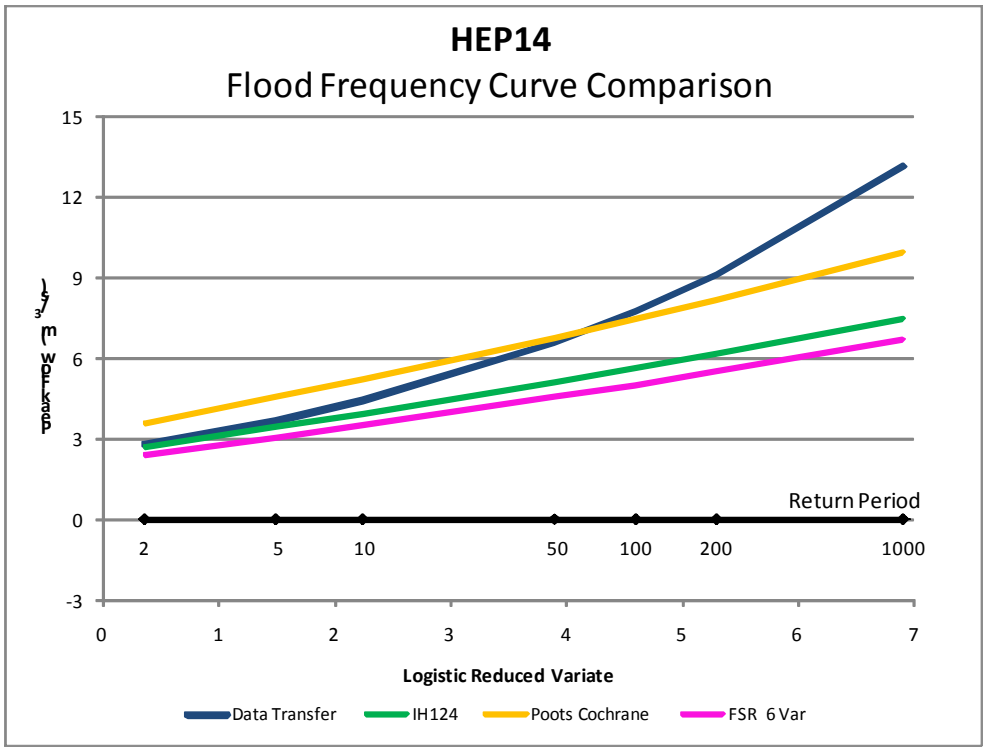


Figure 6-11 - Comparison of design flow estimations for HEP14



6.9.1 Discussion and Recommendations on Small Catchments

The Rational Method is typically applied to small urbanised catchments with times of concentrations of around 30 minutes and times of entry of around 4 minutes. The time to peak for the Bridewell River is in the order of 3 hours and approximately 4 hours for the Millstream. Both watercourses drain mainly rural catchments that are significantly larger than typically used when applying the Rational Method. The study return periods are also in excess of what is typically derived from the Rational Method. Results from this method were found to overestimate expected design flows and are not considered appropriate for further use in this study.

The flows derived from FSR 6, IH124, Poots Cochrane and the FSU data transfer methods are similar for lower return periods (up to 1 in 50 year) for all HEPs; a continued similarity is shown at HEP06 for higher periods, but flows diverge at the other HEPs. At all locations, the flows derived using the Rational Method are significantly higher.

The FSR 6 variable method is typically applied to larger catchments with catchment areas of over 25km^2 and results are presented for comparison. Results show that derived flows were generally found to result in the lowest flow estimation, with the exception for HEP03, where the IH124 method resulted in the lowest flow estimation.

Gardner and Wilcock (2000)[19] reviewed six alternative equations for estimating QBAR, including the Poots Cochrane equation, and tested them on 10 small catchments in Northern Ireland. Of the four equations not calibrated on Northern Irish data, the Poots Cochrane equation was found to fit best, but still underestimated flows in six of the 10 catchments. The comparison undertaken in this study also showed that flows estimated for the 100 year return period were closest to results from the data transfer method.

19 Gardner, C.M.K, Wilcock, D.N. (2000). Predicting the Mean Annual Flood for Small Catchments: Experience in Northern Ireland. CIWEM Water and Environmental Management Journal 14, 253-259.

Cawley and Cunnane (2003)[20] reviewed a number of flow estimation methods used for Greenfield Runoff calculations and found significant uncertainty in the IH124 method. Their paper states that 'In conclusion the poor representation of lower soil classes in the sample and the sensitivity of the regression equation when either three additional catchments of the lower soil types or an alternate minimisation function are included seriously questions of the validity of the IH 124 equation to small catchments and also for soil classes 1 to 3'. The catchments included in this element of the study all fall into soil class 2, so following the findings of Cawley and Cunnane, are likely to be poorly represented by IH124.

The flows were all run through the hydraulic model, and are reported on in the modelling report.

As a result of this comparison, consideration of the applicability of the methods, the data the methods are based on and the model results, we recommend to adopt the design flows based on the FSU data transfer method as inflows to the tributaries.

6.10 Sensitivity Testing & Uncertainty

The process of finalising design flows for use in a hydraulic model is a highly iterative process, involving initial estimates, incorporation of additional data, model simulations and revisions to the flow estimates. For this reason, sensitivity testing of the flows relies on some elements of the hydraulic modelling.

The hydrological flow estimation is also subject to a number of uncertainties, which relate to the estimation of the mean annual flood, the growth curve estimation and the rating curve analysis as well as flow and water level measurements. Factorial Standard Error (FSE) is a measure used to describe uncertainty. It is an approach that the OPW often recommends to assess the potential range of flood flows at a specific location. It is particularly appropriate where a flood estimate is done in isolation, without recourse to a comprehensive calibrated model. Within a CFRAM project FSE can be useful to provide outer bounds of the flood flow estimates. With the analysis on the gauging stations, calibration of the model and a recent large event the uncertainty in the final flow estimate will be much reduced.

6.10.1 Uncertainty of QMED

Applying factorial standard error can be used to calculate confidence intervals (CI). Assuming that errors in the log scale are normally distributed, the 68% confidence interval for QMED will be from QMED/ FSE up to QMED *FSE. And the 95% CI will be QMED/ FSE^2 up to QMED*FSE^2.

When using gauged data to estimate QMED the CI will be determined by the record length and for a record length of 50 year at gauging station 20001 the 95% CI for QMED was estimated between 114 and 133 m^3/s. Applying the FEH method the 95% CI is estimated according to FEH Vol3 Table 12.4 resulting in 118.3m^3/s and 126.5m^3/s. These results show an uncertainty in QMED of up to ±8% and ±4%, respectively.

These results provide a good level of agreement and a high level of confidence due the long annual maximum data record used to derive QMED.

6.10.2 Uncertainty relating to the Bandon Gauge (20001)

The hydrological flow estimation is based on the single site analysis of the Bandon Gauge (20001). The rating curve at Bandon Gauge and the upper and lower bounds were derived by varying the channel and floodplain roughness in the hydraulic model by 20% to provide an indication of the 95% Confidence Intervals (CI) associated with the rating. Figure 6-12 presents results from these stage discharge relationship from these modelling runs..

Sensitivity testing was then undertaken by updating the annual maximum series to the upper CI and lower CI and fitting the statistical distributions for each of the series and undertaking a single site analysis using FEH WINFAP. Table 6-20 present results of the statistical

20 Cawley, T., Cunnane, C. (2003). Comment on Estimation of Greenfield Runoff Rates. National Hydrology Seminar, Ireland.

distribution fitting of the growth factor and Figure 6-13 presents the statistical distribution of the upper annual maximum fitted series.

Table 6-21 presents a comparison of the final design flows at Bandon (HEP04) in comparison to flows derived from the annual maximum series using upper bounds as presented in Figure 6-12.

Results show that the design flows of the 100 year return period are 15% lower than the corresponding flows using the upper CI data.

The sensitivity of the hydraulic model to the differing flows derived from the confidence limits is discussed and illustrated in the Hydraulic Modelling report. However, the modelling results show that flood levels are increased by up to 0.45m at Bandon Town, when comparing final design flows with the flows derived from the upper CI.

Figure 6-12 - Upper & Lower CI at Bandon

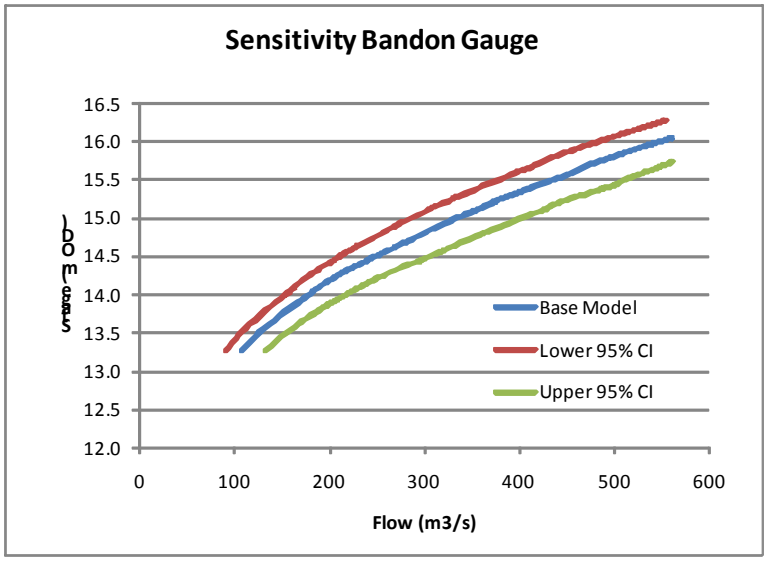


Table 6-20 - Growth Factors using Upper CI

Return Period	L - LMOM	GL - LMOM	G - LMOM	GEV - LMOM	LN2 - MOM	LN3 - LMOM
2	1.08	0.986	1.01	0.979	0.99	0.976
5	1.398	1.328	1.385	1.35	1.405	1.36
10	1.584	1.593	1.634	1.627	1.686	1.641
25	1.809	1.995	1.948	2.018	2.048	2.022
* 50	1.973	2.358	2.181	2.34	2.323	2.324
* 100	2.135	2.788	2.412	2.691	2.601	2.64
* 200	2.295	3.297	2.643	3.074	2.885	2.973
* 500	2.666	4.89	3.177	4.105	3.572	3.816

Figure 6-13 - Fitted Distribution of the Updated AMax using the Upper CI

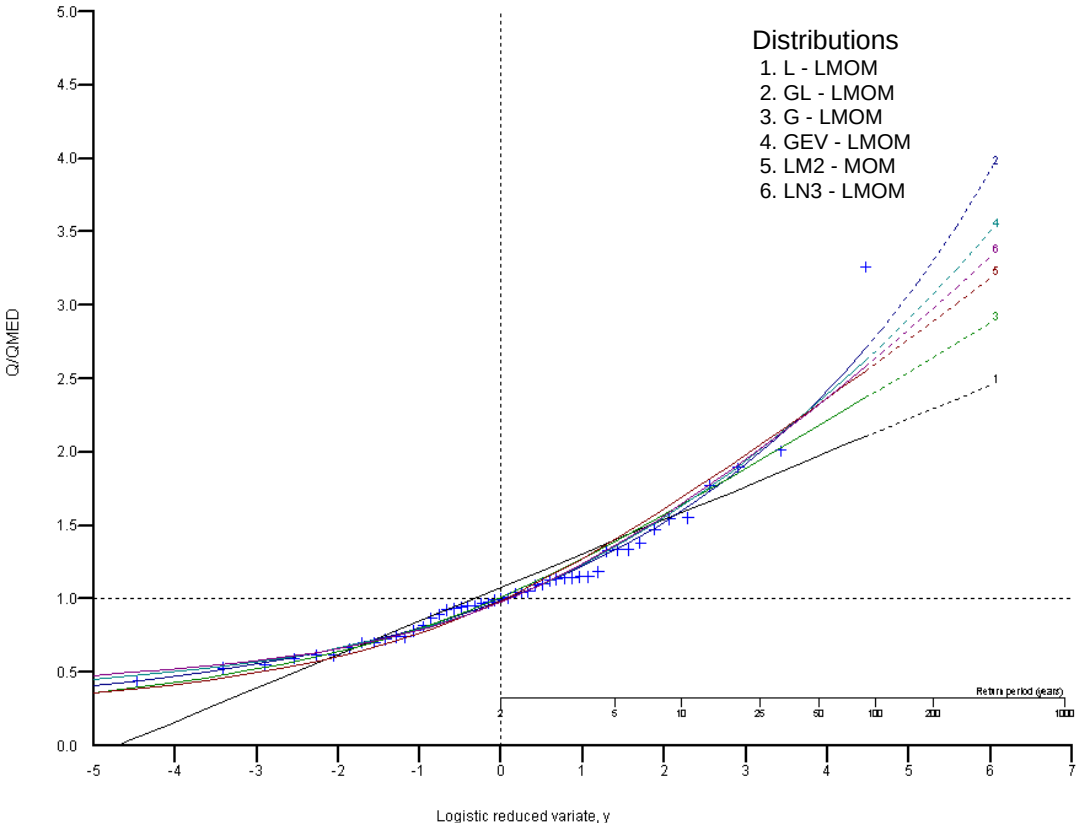


Table 6-21 - Comparison of Final Design Flows at Bandon (HEP04) (m^3/s) with Upper CI

Return Period	2	5	10	50	100	200
Final Design Flows at Bandon (HEP04)	122	162	194	288	339	399
% difference to Upper CI	16%	19%	20%	17%	15%	12%
Upper CI GEV - LMOM	145	200	241	347	399	456
Absolute difference to Final Flows	23	38	47	59	60	57

6.10.3 Uncertainty of the Growth Curve

The confidence limit relating to the growth curve was estimated for the single site analysis at the Bandon Town Gauge using FEH-WINFAP and applying the GEV distribution. Table 6-22 presents the upper and lower confidence interval for the growth curve at Bandon.

Results show that the growth factor for the 100 year return period, including the 95% Confidence Interval is comparable to the growth factor for the 1000 year return period derived from the single site analysis.

Table 6-22 - 95% Confidence limit on growth curve

Return Period	Growth Factor Single Site Analysis	Growth Factor for lower and upper Confidence Intervals
2	1.00	0.90 - 1.04
5	1.33	1.14 - 1.45
10	1.60	1.30 - 1.86
25	2.01	1.52 - 2.63
50	2.37	1.65 - 3.48
100	2.79	1.82 - 4.57
200	3.28	1.95 - 5.99
1000	4.73	2.16 - 11.50

6.10.4 Application of Factorial Standard Error

In order to provide additional confidence in any future bridge or culvert sizing, the 95% confidence limit (CI) on the growth curve was applied to the proposed design flow estimates, as this provides the most conservative design flow estimates. Table 6-23 presents the final design flow estimates (95%CI) for all HEPs to be applied for bridge or culvert sizing.

Table 6-23 - Final Design flow for bridge or culvert sizing (95%CI)

Return Period	Growth Factor 95%CI	HEP01	HEP02	HEP03	HEP04	HEP05	HEP06	HEP07	HEP08	HEP09	HEP10	HEP11	HEP14	HEP15	HEP16	HEP17
2	1.04	116	117	4.9	122	4.3	0.7	3.0	129	14.4	135	1.5	2.8	1.6	15.2	1.0
5	1.45	169	169	7.1	176	6.2	1.1	4.4	187	20.9	196	2.2	4.0	2.3	22.0	1.5
10	1.86	217	217	9.1	226	8.0	1.4	5.7	240	26.8	251	2.8	5.2	3.0	28.2	1.9
20	2.63	306	307	12.8	320	11.3	2.0	8.0	339	37.8	355	4.0	7.3	4.2	39.9	2.7
50	3.48	405	407	16.9	423	14.9	2.6	10.6	449	50.1	470	5.2	9.7	5.5	52.8	3.6
100	4.57	532	534	22.3	556	19.6	3.4	13.9	589	65.8	618	6.9	12.7	7.3	69.3	4.7
200	5.99	698	700	29.2	728	25.7	4.5	18.2	772	86.2	810	9.0	16.6	9.5	90.8	6.1
1000	11.5	1340	1344	56	1398	49.4	8.6	35.0	1483	165.5	1554	17.3	31.9	18.3	174.4	11.8

Results show that the design flows for the 100 year return period, including the 95% Confidence Interval is comparable to the recommended 1000 year return period flows for the scheme design (see Table 6-15), providing precautionary allowance for uncertainty. Therefore it is recommended to adopt the 0.1% AEP flows to test for robustness of any flood mitigation measures.

7. Future Environmental and Catchment Changes

7.1 Potential Catchment Changes

Across the catchment, the factors that cause flooding and the resulting damages will change in the future. So that the approach to flood risk management is sustainable, the likely changes and how catchments are likely to respond must be identified. This will enable informed decisions about long-term flood risk management in the Bandon catchment to be made. There are three main factors that could affect future flood risk:

- climate change;
- urban development; and
- land use management.

7.2 Climate Change

The DoEHLG and OPW guidelines, The Planning System and Flood Risk Management[21], recommend that a precautionary approach is adopted due to the level of uncertainty regarding the potential effects of climate change. A significant amount of research into climate change has been undertaken both nationally and internationally. This section will briefly examine some of the key findings of the research to date.

The Intergovernmental Panel on Climate Change (IPCC) was established in 1988 and its first report in 1990 justified concern about the effects of climate change on a scientific basis. The more recent IPCC Fourth Assessment Report 2007[22] concludes that climate change is unequivocal. It projects a global average sea level rise of between 0.18m and 0.59m for different SRES emissions scenarios[23], up to the end of the century.

More specific advice on the expected impacts of climate change and the allowances to be provided for future flood risk management in Ireland is given in the OPW draft guidance[24]. Two climate change scenarios are considered. These are the Mid-Range Future Scenario (MRFS) and the High-End Future Scenario (HEFS). The MRFS is intended to represent a "likely" future scenario based on the wide range of future predictions available. The HEFS represents a more "extreme" future scenario at the upper boundaries of future projections. Based on these two scenarios the OPW recommended allowances for climate change are given in Table 7-1.

Table 7-1 - Allowances for Future Scenarios (100 Year Time Horizon)

Parameter	MRFS	HEFS
Extreme rainfall depths	+20%	+30%
Flood flows	+20%	+30%
Mean sea level rise	+500mm	+1000mm
Land movement	-0.5mm / year*	-0.5mm / year*
Urbanisation	No general allowance - Review on case by case basis	No general allowance - Review on case by case basis
Forestation	-1/6 Tp** No change to SPR	-1/3 Tp** +10% SPR***

Notes:
* Applicable to the southern part of the country only (Dublin - Galway and south of this)
** Reduce the time to peak (Tp) by a third; this allows for potential accelerated runoff that may arise as a result of drainage of afforested land
*** Add 10% to the Standard Percentage Runoff (SPR) rate; this allows for increased runoff rates that may arise following felling of forestry

[21] DoEHLG and OPW, The Planning System and Flood Risk Management: Guidelines for Planning Authorities (2009)
[22] Inter-Governmental Panel on Climate Change (IPCC), 4th assessment report. "Climate Change 2007"
[23] Inter-Governmental Panel on Climate Change (IPCC),Special Report on Emissions Scenarios, 2000
[24] OPW Assessment of Potential Future Scenarios, Flood Risk Management Draft Guidance, 2009

7.3 Urban Development

The amount of water that falls as rain cannot be controlled, but its movement across the land and through rivers can be managed. The way land is used can speed up or slow down the passage of water to rivers and also affects how much water is stored at the surface. It is important to consider the location and extent of urban land to help understand future flood risk because:

- urbanisation of previously undeveloped land (greenfield) increases the cover of impermeable surfaces so that more runoff is generated during rainfall events and water moves quickly into watercourses;
- urban land keeps water at the surface and this water has to be managed using urban drainage systems;
- development and regeneration of previously undeveloped land within the existing floodplain can increase flood risk.

Under the County Development Plan[25], all new developments should incorporate Sustainable Drainage Systems (SuDS) to reduce direct runoff, for example by directing water into soakaways or storage areas. Although this will help to reduce the impact of development, flood risk will still increase in the future.

Less than 1% of the River Bandon catchment area is urbanised, and Bandon itself forms one of the two main settlements. In the draft Local Area Plan (LAP)[26], Bandon is identified as a main settlement within the Bandon Electoral Area, and retains its status as a ring town in the overall strategy of Volume 1 of the County Development Plan. The current housing stock in Bandon (as recorded in 2010) is 2553. The LAP set the new house construction target for Bandon to 1485 units by 2020.

Dunmanway is the other main town within the River Bandon catchment, and is located in the upper part of the catchment. Development targets for Dunmanway are given in the draft Skibbereen Local Area Plan[27]. The current potential housing stock (including those under construction) is 868, with a projected 194 additional houses required by 2020.

Although representing an overall increase in both settlements of approximately 61%, the overall scale of development is small. It is also important to note that development within Bandon and its immediate surroundings will have less impact on flood flows that development in the upstream catchment.

The FSU includes an urban factor, which represents the percentage urban land cover within the catchment. By changing the proportion urbext in the FSU equation, the increase in flows resulting from changes in urbanisation can be investigated. As shown in Section 6.2, the current level of urbanisation results in an increase of approximately 2m^3/s at HEP 4 when compared to the rural scenario. Table 7-2 shows the impact of further increases in urbanisation, with both the impact of 60% increase in the current levels of urbanisation (i.e. the projected increases contained in the current development plans), and the impact of 10% of the catchment becoming urbanised. Given that less than 1% of the catchment is currently urbanised, this represents a highly improbable scenario.

Table 7-2 - Increase in Urbanisation

	HEP 04 (Bandon)
Qmed rural	140.9
Qmed urban (current percentage)	142.6
Qmed urban (60% increase)	143.5
Qmed urban (10% of catchment urbanised)	162.3

[25] Cork County Council, County Development Plan, Adopted 2009
[26] Bandon Draft Local Area Plan, Cork County Council, 2010
[27] Skibbereen Draft Local Area Plan, Cork County Council, 2010

Further, the use of runoff mitigation measures and SuDS, as part of urban development schemes will reduce risk. However there are considerable practical, legal and adoption difficulties in implementing SuDS which will need to be addressed.

It is therefore considered unlikely that urban development will increase flood risk in the catchment to any degree, provided mitigation measures are incorporated within any development.

7.4 Land Use Management

Agricultural land use and land management have the potential to influence runoff generation and sediment production. The type of crops that are grown, the way the land is managed and changes in agricultural drainage practice affect how quickly water reaches rivers and the amount of silt that gets washed into rivers during rainfall events.

Much of the River Bandon catchment is rural, with over 82% of the catchment given over to agricultural land, so the effect of agricultural practices on flood risk could be quite significant, particularly if all the farms in the catchment intensified production. However, if intensification is to occur, it would probably take place on individual farms rather than across the whole catchment, so is unlikely to have a great net impact.

Deforestation and afforestation can potentially influence flood risk by affecting surface runoff. The County Development Plan has "an objective generally to support forestry development throughout the County subject to normal planning considerations, sustainable development criteria and the principles and objectives of this plan". Approximately 11% of the catchment is woodland, so there may be opportunities for expanding this cover through increased forestry, with impacts for flood risk management. Although the theory of forests acting as sponges soaking up water is popular, scientific studies have shown that the influence of forests on flooding and runoff is more complex[28]. Most of the well-known experimental hydrological studies of forestry have been undertaken in the UK, and have been on upland catchments, primarily investigating plantation forestry. In such cases, the effects of the forestry on runoff have been complicated by the influence of drainage ditches dug before the trees were planted.

Perhaps because of the complications of the crop cycle and management practices (such as drainage), there is little evidence from regional flood studies that the area covered by forest is a significant independent variable in the regression equations used for flood estimation[29]. However, this does not mean that forests have no effect on a local scale. Forests and forest soils (with their deep litter layer) are capable of storing and transpiring more water than grassland or arable crops. Therefore, in the absence of complicating factors such as drainage, one can expect a reduction in downstream flood volumes and an increase in time to peak. Changing the time to peak can be a particular concern in areas where flood risk is exacerbated when two tributaries peak at the same time. Conversely, in some areas, changing the time to peak, for example through creation of attenuation areas of one tributary, can stop the peaks coinciding, and therefore reduce flood risk. In the Bandon catchment, coincidence of peak flows has not been demonstrated to be a significant contributor to current or potential future flood risk. However, a significant change in time to peak on the River Bandon will impact on the lead times used in FEWS (Flood Early Warning System).

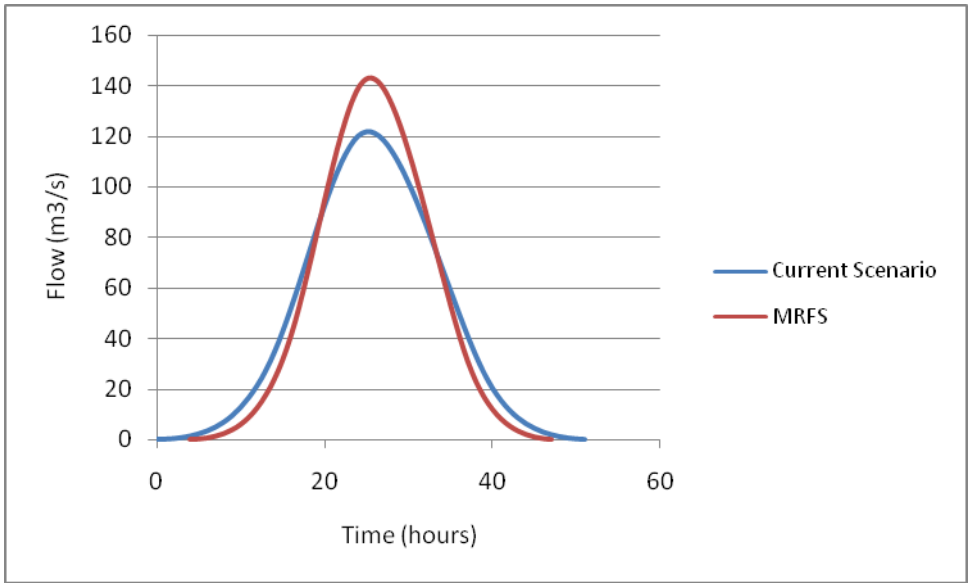
There are a number of ways that land use within the catchment could change in the future, depending on the full impact of climate change on the rest of the country, government policies and local industry drivers. Under the OPW MRFS, it is recommended that the impacts of afforestation are investigated through a decrease in time to peak of a sixth; this allows for potential accelerated runoff that may arise as a result of drainage of afforested land. This means the volume of water in the river is unchanged, but the rate at which it runs of the land into the watercourse is increased.

[28] UNFAO Center for International Forestry Research (2005). Forests and Floods. UNFAO.
[29] Institute of Hydrology (1991). Plynlimon research: The first two decades. Report No. 109, Institute of Hydrology.

As shown in Figure 7-1, the impact of increased afforestation, based on the MRFS, has a significant impact on peak flows. However, changing the time to peak to take account of change in land management is extremely generic. Although it may be perceived that an activity only has one impact, the run-off generation mechanisms vary considerably through the lifetime of the plantation, and depending on the specific management practices (relating to drainage and felling cycles) which are operated). A generic decrease in Tp does not take into account the spatial distribution of such changes. It also fails to account for the impact of different kinds of planting; increased runoff is more likely to occur as a result of commercial conifer plantations that the creation of broadleafed woodlands (which have been shown to reduce runoff through generation of an active litter layer).

It is currently not possible to relate the generic increase in Tp to a specific quantity of afforestation. Generic change factors also fail to account for the conflicting impacts of different land management practices; for example the creation of insensitive ever-green forests in one part of the catchment may be balanced by afforestation, or other management practice, in another.

Figure 7-1 - Impact of afforestation on HEP04 for QMED



Land management and its impact on flood risk is currently an active topic of research in academic and government sectors, but spatially distributed modelling techniques, of the kind required to determine the specific impact of land management changes across a catchment, are not currently available.

7.5 Summary

Climate change, urbanisation and land use change have been identified as potential sources of change in the River Bandon catchment over the next 100 years. A review of the current land use and an assessment of the scale of likely changes has indicated that only climate change is likely to impact in a significant and modellable way on the hydrological regime of the catchment.

Therefore, the final design flows will be increased to account for both the MRFS and HEFS projections of increases in the statistical flow peaks, to test the sensitivity of the current hydraulic regime and any potential flood management solutions.

Appendices

A. Flood Hazard Mapping Report

OPW *National Flood Hazard Mapping*

Summary Local Area Report

This Flood Report summarises all flood events within 2.5 kilometres of the map centre.

The map centre is in:

County: Cork

NGR: W 495 554

This Flood Report has been downloaded from the Web site www.floodmaps.ie. The users should take account of the restrictions and limitations relating to the content and use of this Web site that are explained in the Disclaimer box when entering the site. It is a condition of use of the Web site that you accept the User Declaration and the Disclaimer.

Map Scale 1:62,129

Map Legend
Flood Points
Multiple / Recurring Flood Points
Areas Flooded
Hydrometric Stations
Rivers
Lakes
River Catchment Areas
Land Commission *
Drainage Districts *
Benefiting Lands *

* Important: These maps do not indicate flood hazard or flood extent. Thier purpose and scope is explained in the Glossary.

15 Results

1. Bandon Flooding November 2009	Start Date: 19/Nov/2009
County:Cork	Flood Quality Code:2
Additional Information: Reports (2) More Mapped Information	
2. Bandon Bandon Town August 1986	Start Date: 05/Aug/1986
County:Cork	Flood Quality Code:3
Additional Information: Reports (2) Press Archive (9) More Mapped Information	
3. Bandon November 1916	Start Date: 16/Nov/1916
County:Cork	Flood Quality Code:4
Additional Information: Reports (1) Press Archive (1) More Mapped Information	
4. Bandon Co.Cork 15th January 2011	Start Date: 15/Jan/2011
County:Cork	Flood Quality Code:4
Additional Information: Reports (1) More Mapped Information	
5. Bandon Bandon Town Oct 1975	Start Date: 22/Oct/1975
County:Cork	Flood Quality Code:3

Report Produced: 24-Mar-2011 14:29

Additional Information: Reports (1) Press Archive (13) More Mapped Information

6. River Bandon tributary R603 Recurring — Start Date:
County: Cork — Flood Quality Code:4
Additional Information: Reports (1) More Mapped Information

7. River Bandon Glasslinn Road Bandon Recurring — Start Date:
County: Cork — Flood Quality Code:4
Additional Information: Reports (1) More Mapped Information

8. River Bandon N71 Innishannon Road Recurring — Start Date:
County: Cork — Flood Quality Code:4
Additional Information: Reports (1) Press Archive (4) More Mapped Information

9. River Bandon floodplain at Kilbeg Recurring — Start Date:
County: Cork — Flood Quality Code:4
Additional Information: Reports (1) More Mapped Information

10. River Bandon Bank Place Bandon Recurring — Start Date:
County: Cork — Flood Quality Code:4
Additional Information: Reports (1) More Mapped Information

11. River Bandon Brady Lane St Finbarr's Recurring — Start Date:
County: Cork — Flood Quality Code:4
Additional Information: Reports (1) More Mapped Information

12. River Bandon Weir St McSweeney Quay Recurring — Start Date:
County: Cork — Flood Quality Code:4
Additional Information: Reports (1) Press Archive (2) More Mapped Information

13. River Bandon floodplain north of Gully Recurring — Start Date:
County: Cork — Flood Quality Code:4
Additional Information: Reports (1) More Mapped Information

14. Bandon River, Bandon, Co. Cork Recurring — Start Date:
County: Cork — Flood Quality Code:4
Additional Information: Reports (1) Press Archive (20) More Mapped Information

15. River Bandon South Main St Pearse St Recurring — Start Date:
County: Cork — Flood Quality Code:4
Additional Information: Reports (1) Press Archive (3) More Mapped Information

Report Produced: 24-Mar-2011 14:29

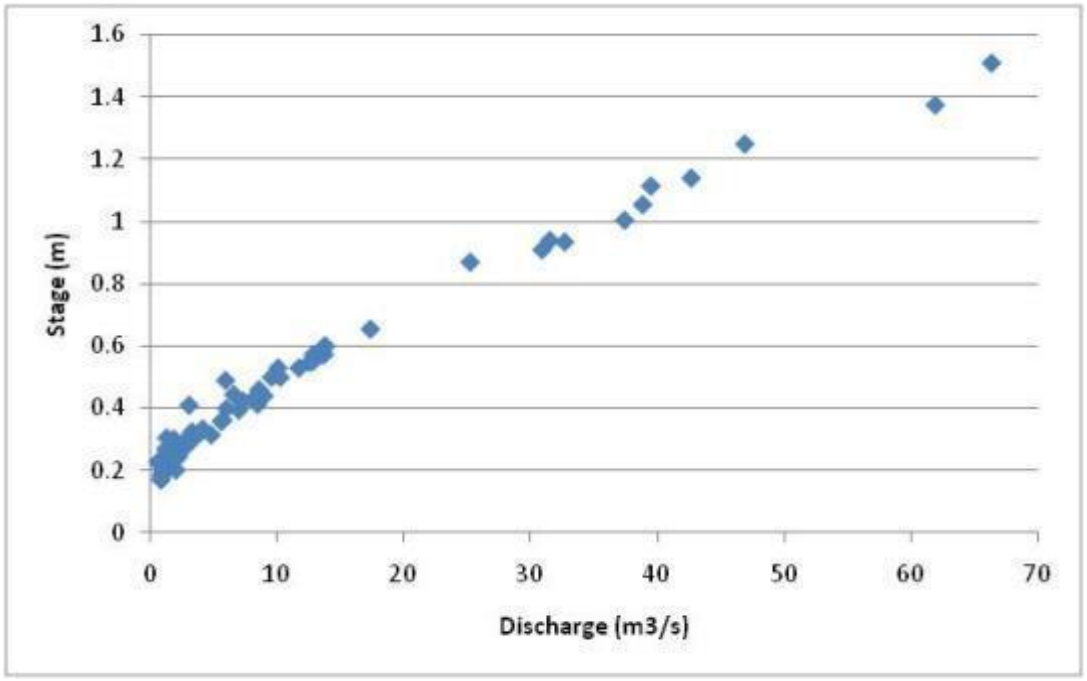
B. Gauging Station Review

B.1 Gauge - 20003 (Inishannon)

The gauging station on the River Bandon at Inishannon is an inactive staff gauge which was monitored by the EPA. The gauge is located at grid reference 153784 57329 (ING) approximately 400m upstream of the Inishannon bridge. Continuous records are not available for this gauge, but spot gaugings for the period September 1975 to February 1998 have been provided. The gauge datum is 4.362 mOD (Poolbeg) or 1.652 mOD (Malin).

This gauge is within the modelled reach of the River Bandon, lying within a MPW. The range of flows is similar to those covered by the OPW gauge, 20002.

Gauge 20003 Ratings



B.2 Gauge - 20004 (U/S Manch Bridge)

The gauging station on the River Bandon upstream of Manch Bridge is also an obsolete staff gauge which was monitored by the EPA. The gauge is located at grid reference 127802 51894 (ING) approximately 1.8km upstream of the Manch Bridge and immediately upstream of a ford crossing point. It is approximately 5.2km downstream of Dunmanway. Continuous records are not available for this gauge, but 20 spot gaugings were taken between July 1977 and February 1988.

In light of the lack of information, and the gauge's location upstream of the modelled reach, this gauge will not considered further in this study.

B.3 Gauge - 20007 (Ballineen)

The gauging station on the River Bandon at Ballineen is also an inactive staff gauge which was monitored by the EPA. The gauge is located at grid reference 134283 53872 (ING) approximately 80m upstream of the Ballineen Bridge. Continuous records are not available

for this gauge, and only two flow gaugings were recorded (in July 1989 and August 1990) but corresponding levels are not available.

Although there are number of recordings, the gauge is located a considerable distance upstream of the modelled reach, so this gauge will not be considered further in this study.

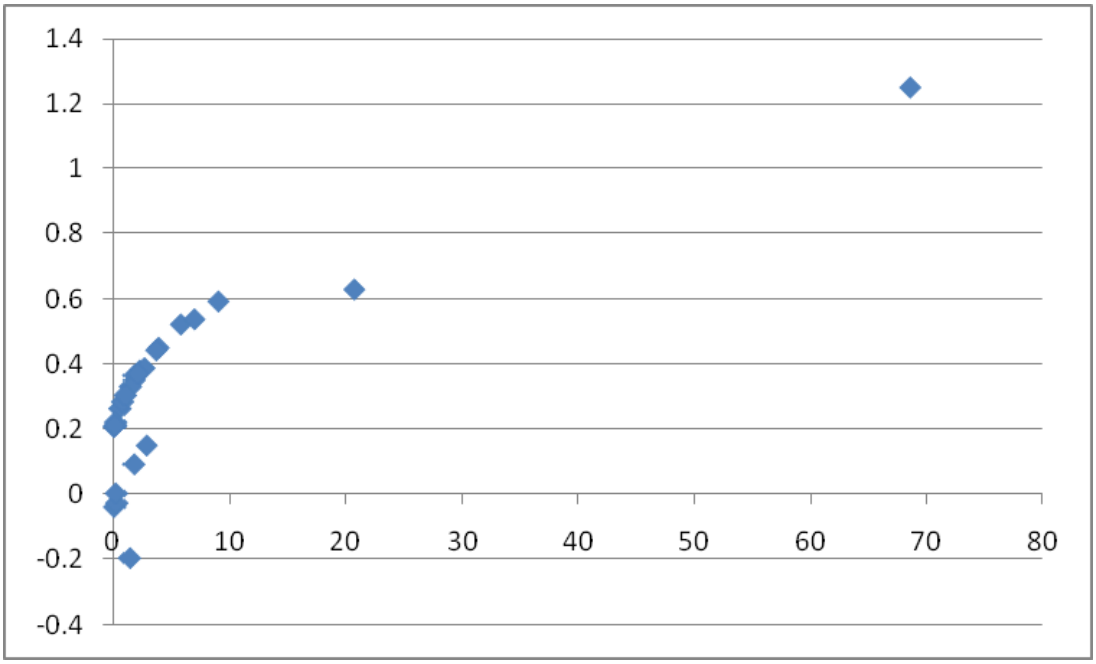
B.4 Gauge - 20008 (Long Bridge, Dunmanway)

The gauging station on the River Bandon at Long Bridge, Dunmanway is a continuous level gauge, which is under the control of the OPW. The gauge is located at grid reference W 241 529 (ING) approximately 100m downstream of the Long Bridge.

Continuous level records are available from January 1991 to date. Spot gaugings have also been taken, with 29 measurements taken between July 1977 and October 2004 .

The gauge is located in the upper portion of the catchment, and is upstream of the modelled reach within Bandon. Although it is a continuous recorder, it is of limited use to the study as it is so far upstream of the study area.

Gauge 20008 Ratings



B.5 Gauge - 20010 Carrigmore

The Carrigmore gauging station is on the River Blackwater, one of the tributaries of the River Bandon. The gauge is on Water Bridge, on the R586 at 131733, 53404 (ING), immediately upstream (approximately 120m) of the confluence with the Bandon.

The gauge is now inactive, but 73 spot gauging measurements were taken between September 1979 and July 2009. The gauge is upstream of the study area at the downstream end of a sub catchment which is not being including as an explicit inflow to the model; the gauge will therefore not be examined further in this study.

B.6 Gauge - 20011 (Downdaniel Bridge)

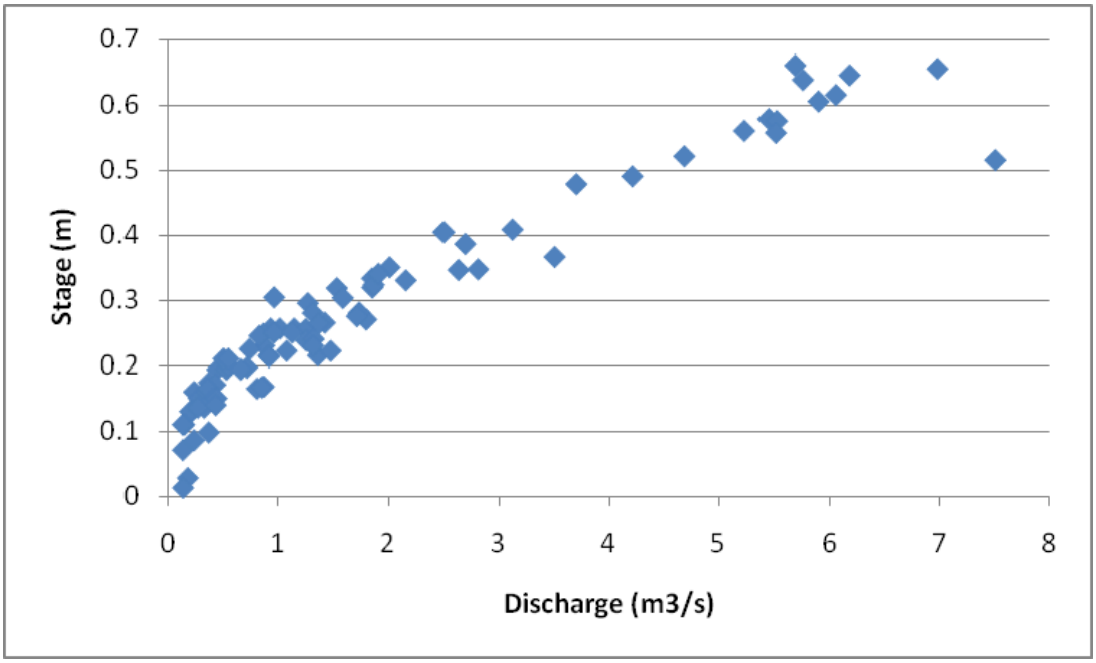
The staff gauge at Downdaniel Bridge is at the downstream end of the Brinny River, another tributary of the River Bandon. The gauge is located at 153129 57380, approximately 100m

from the confluence. The confluence of the Brinny and the Bandon is within the study area, between Bandon town and Inishannon, and the Brinny River itself is a MPW.

The gauge is active, and 78 spot measurements have been recorded since June 1975; the most recent being September 2010. The gauge datum is 3.477 mOD (Malin).

This gauge is within the modelled reach of the River Bandon, lying within a MPW. The gaugings may be used to assist in the calibration of the model.

Gauge 20011 Ratings



B.7 Gauge - 20013 (Carbery M.P)

The Carbery M.P gauging station is on the River Bandon at 132998, 53714 (ING), approximately 1.5km upstream of Ballineen.

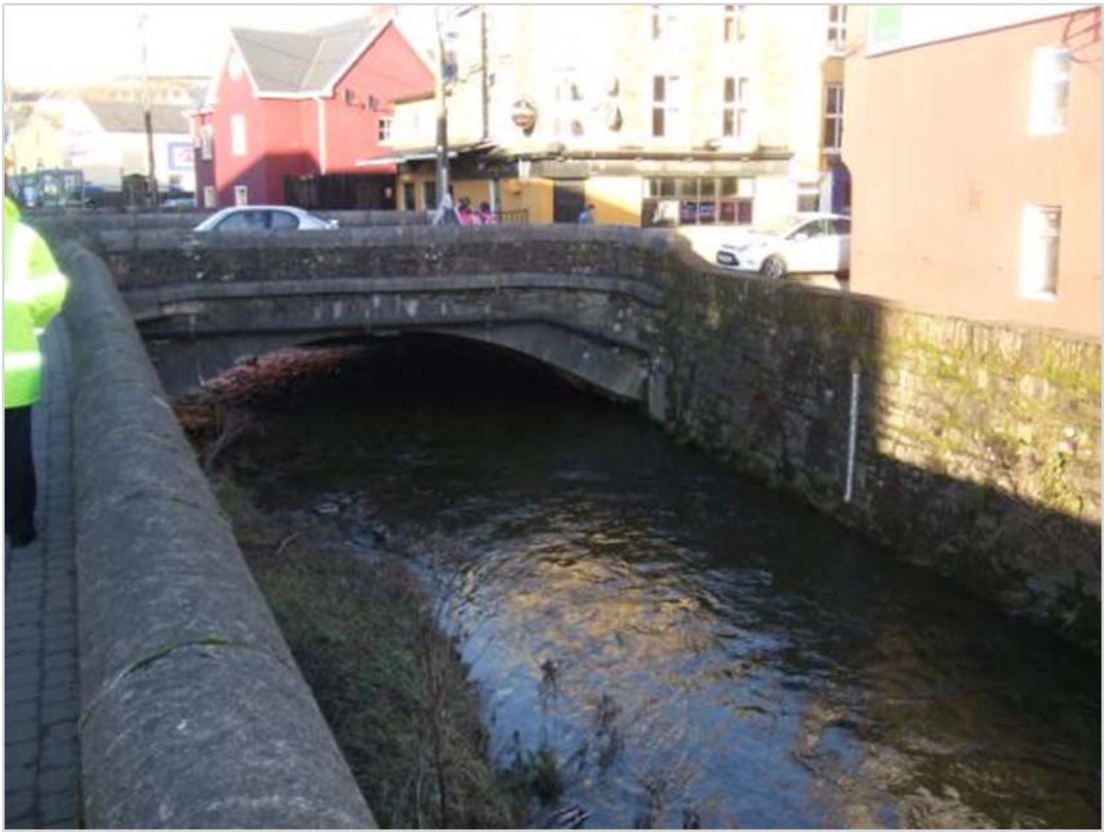
The gauge is now inactive, but 32 spot gauging measurements were taken between May 1981 and September 1999. Although there are number of spot recordings, the gauge is located a considerable distance upstream of the modelled reach, so this gauge will not be considered further in this study.

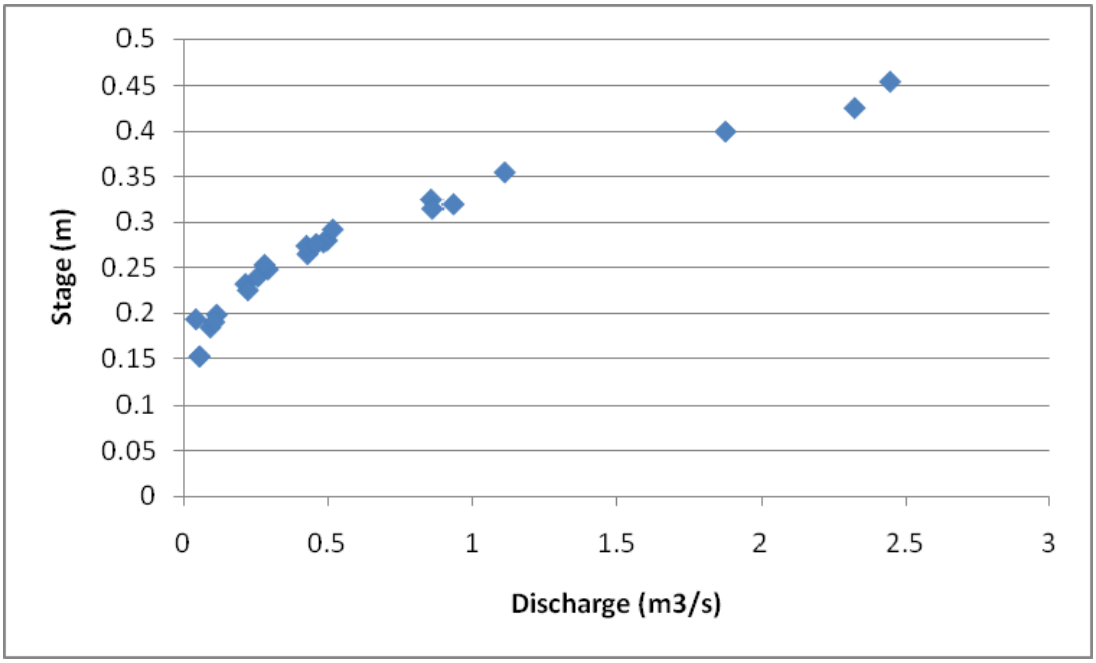
B.8 Gauge - 20014 (Clockmasimon)

The staff gauge at Clockmasimon is at the downstream end of the Bridewell River, a tributary of the River Bandon. The gauge is located at 149019, 54663 (ING), approximately 500m from the confluence of the two rivers. The confluence of the Bridewell and the River Bandon is in the centre of Bandon Town, and the Bridewell is a known source of fluvial flooding. The Bridewell River is a HPW, and the gauge is located within the 2D model domain.

Although 24 spot measurements were recorded between August 1990 and April 1998, the gauge is currently inactive and the zero datum level is unknown. The gauge will therefore not be used in the study.

Gauge 20014 Location and Ratings





B.9 Gauge - 20015 (Ardcahan Bridge)

The gauging station on the River Bandon at Ardcahan Bridge is upstream of Dunmanway, at 124321, 55734 (ING). It is immediately downstream of the confluence of the Bandon and

Caha Rivers. The gauge is a continuous level recorder, which is under the control of the OPW; 15 minute level records are available from May 1999 to date.

The gauge is located in the upper portion of the catchment, and is upstream of the modelled reach within Bandon, but may be used a member of a pooling group for the development of a local growth curve.

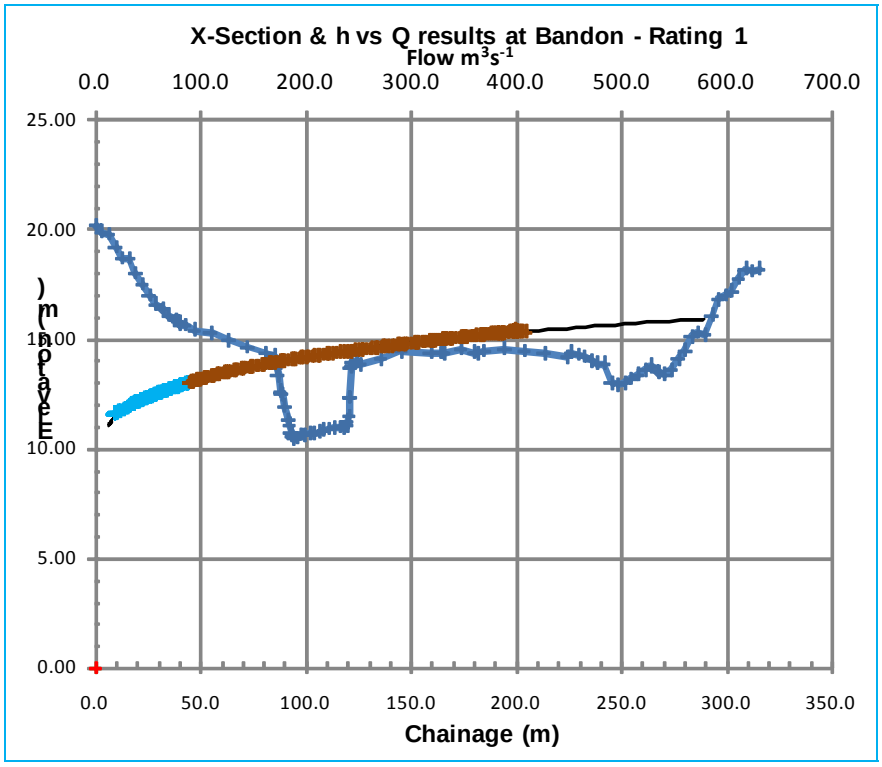
B.10 Gauge - 20016 (Bealaboy Bridge)

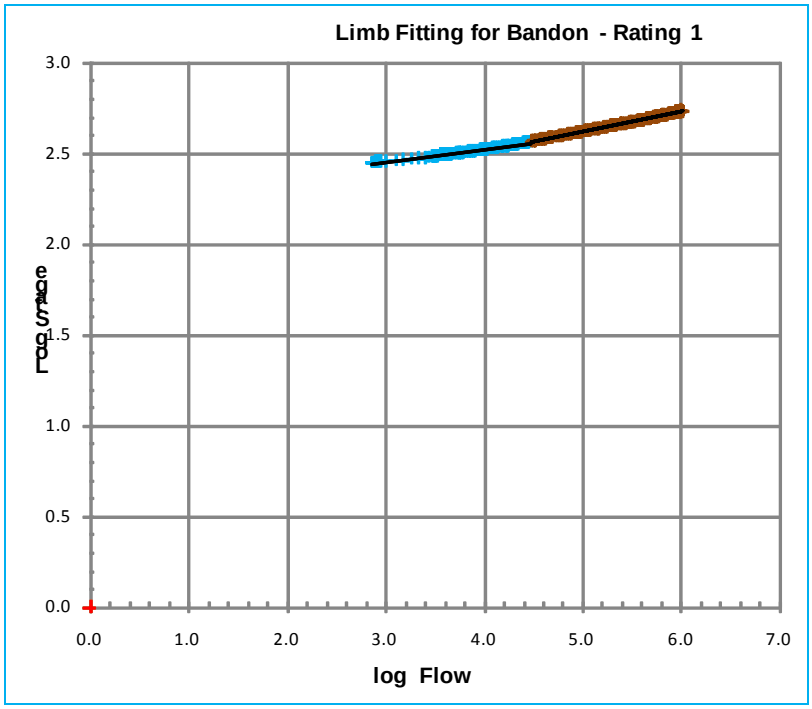
The Bealaboy Bridge gauging station on the River Bandon downstream of Dunmanway is a continuous level gauge, which is under the control of the OPW. The gauge is located at grid reference 125599, 51282 (ING) approximately 80m upstream of the Bealaboy Bridge. Continuous (15 minute) level records are available from May 1990 to date.

The gauge is located in the upper portion of the catchment, and is upstream of the modelled reach within Bandon, but may be used a member of a pooling group for the development of a local growth curve.

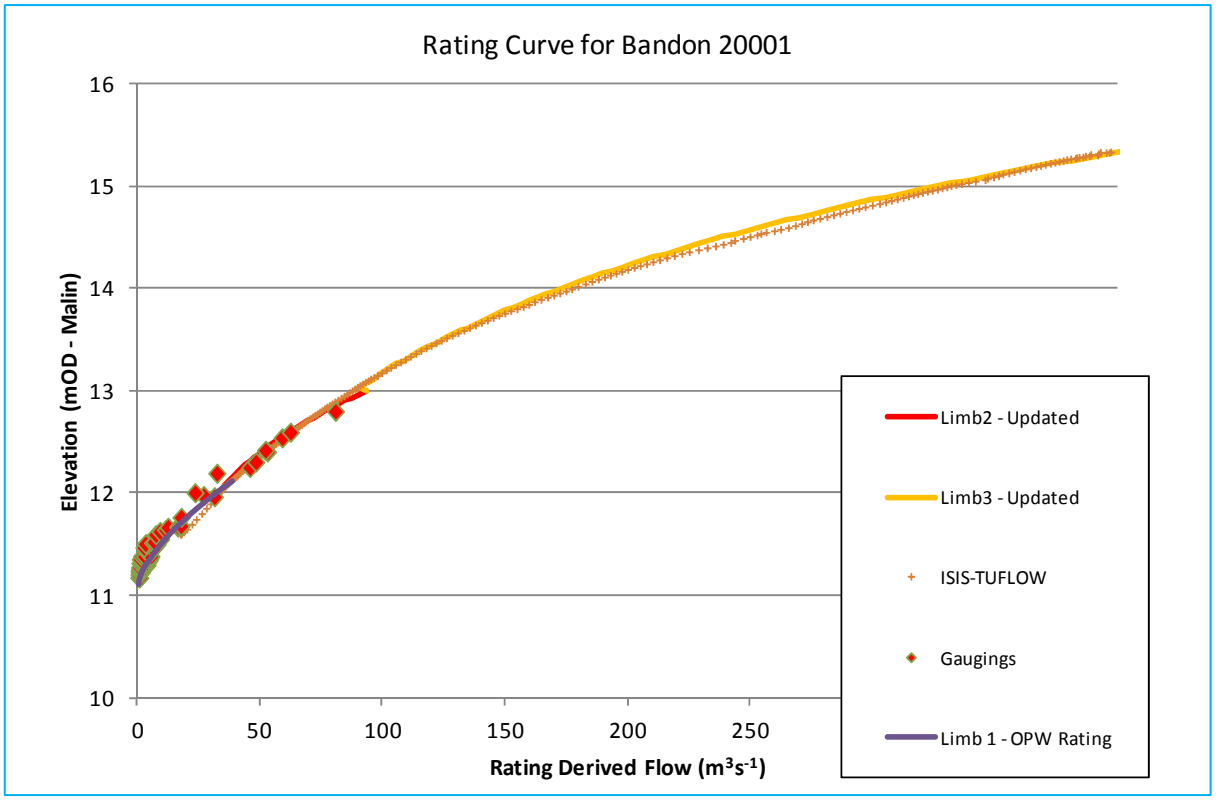
C. Rating Review

C.1 Bandon (20001)

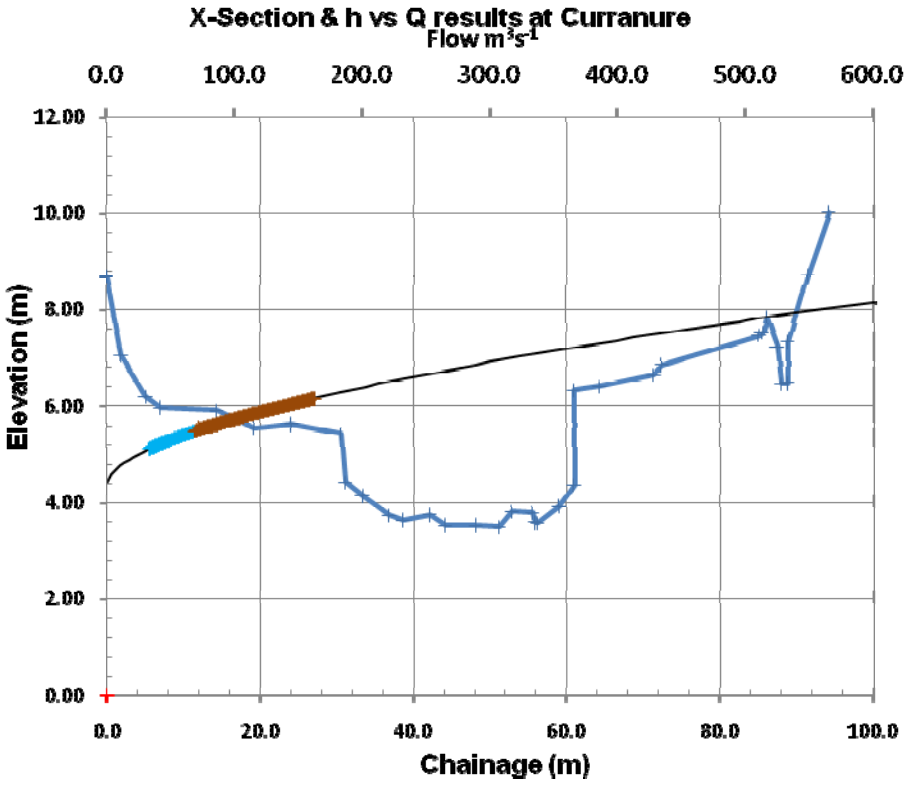


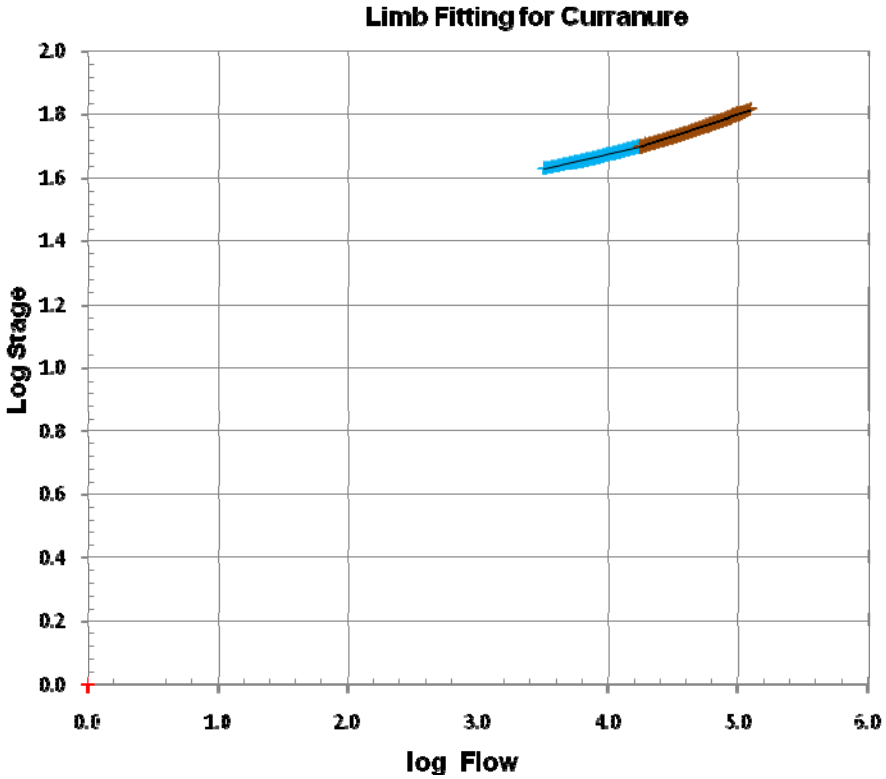


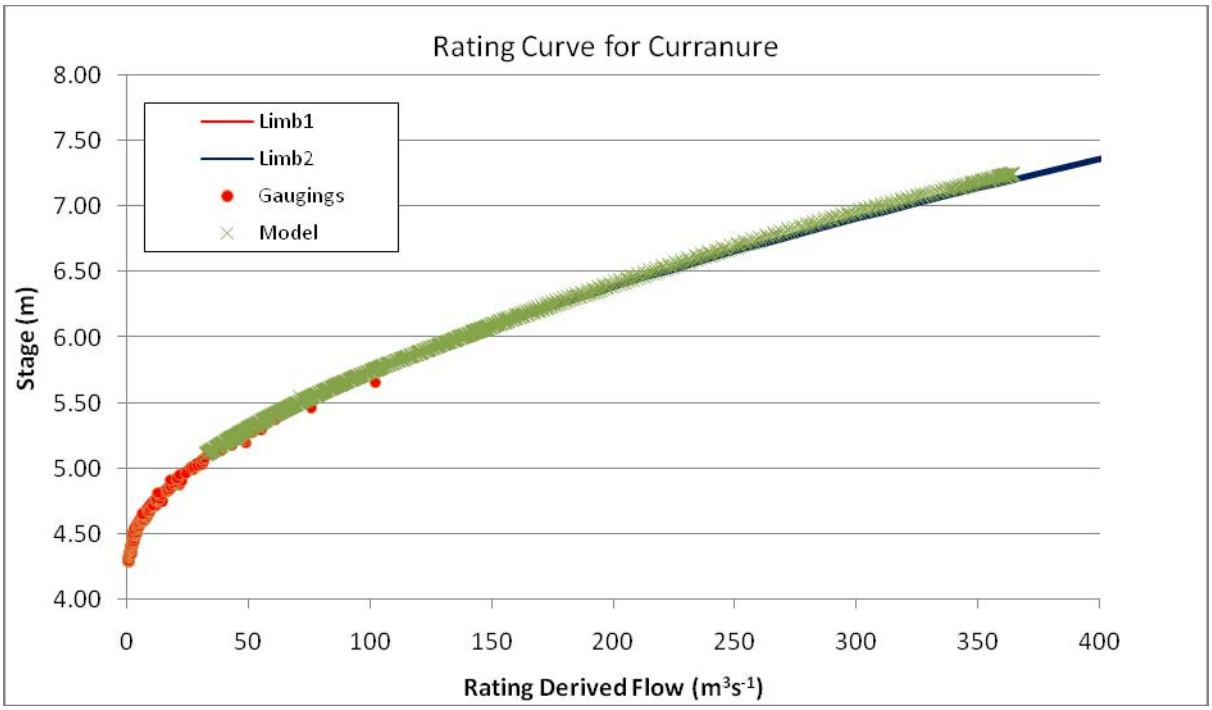
Limb No.	c	a	b	Stage range (m) Min	Max	r2	Log Max Stage
1 - OPW Rating	33.80	0.1090	1.64	11.10	12.00	NA	1.08
2 - Updated	5.8E-29	-8.9740	22.52	12.00	13.00	0.834	2.565
3 - Updated	3.1E-17	-7.6200	14.05	13.00	16.00	0.950	2.773



C.2 Curranure (20002)





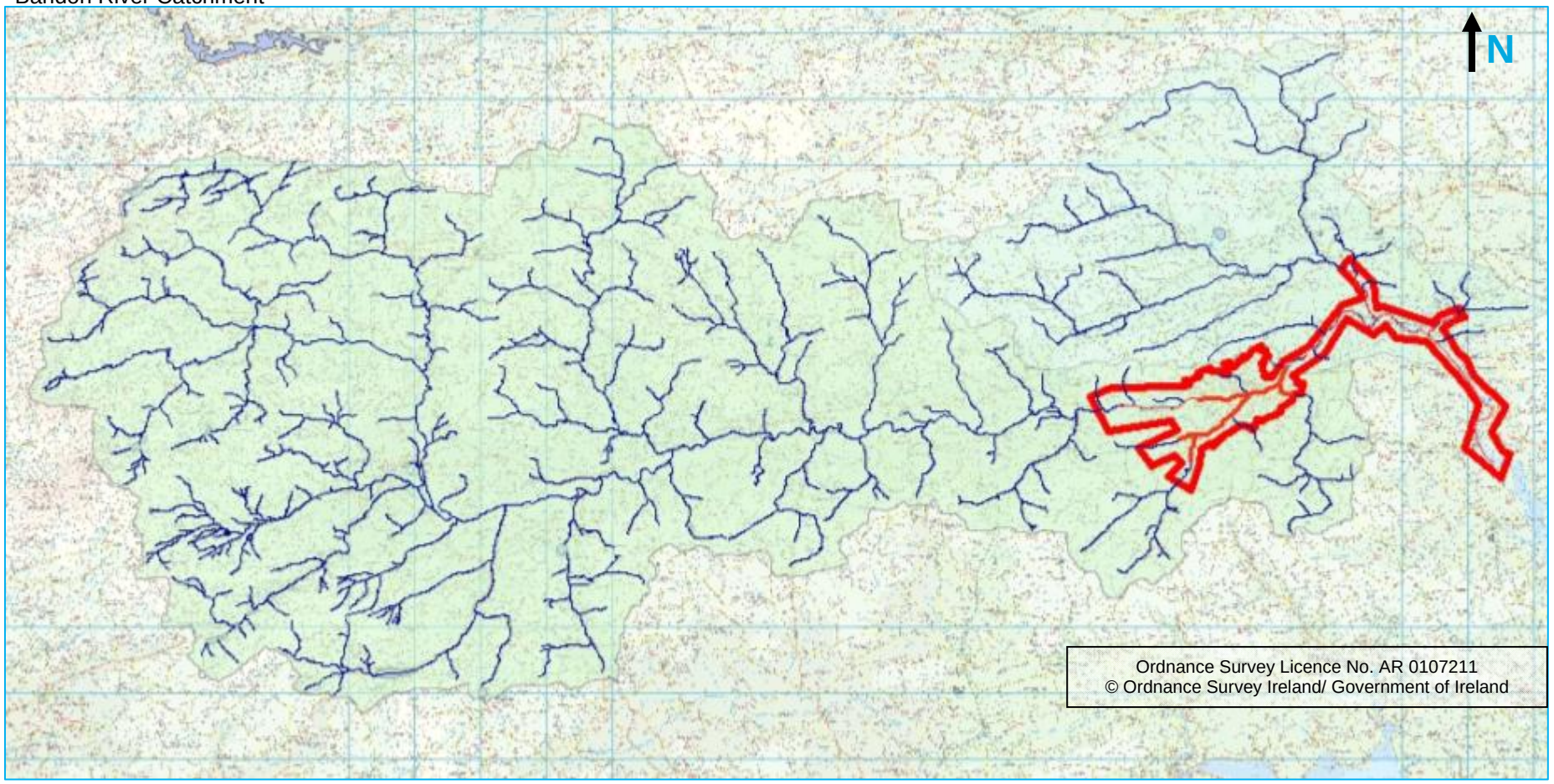

Rating Curve for Curranure
8.00
7.50
7.00
6.50
6.00
5.50
5.00
4.50
4.00
Stage (m)
Limb1
Limb2
Gaugings
Model
0
50
100
150
200
250
300
350
400
Rating Derived Flow (m3s-1)

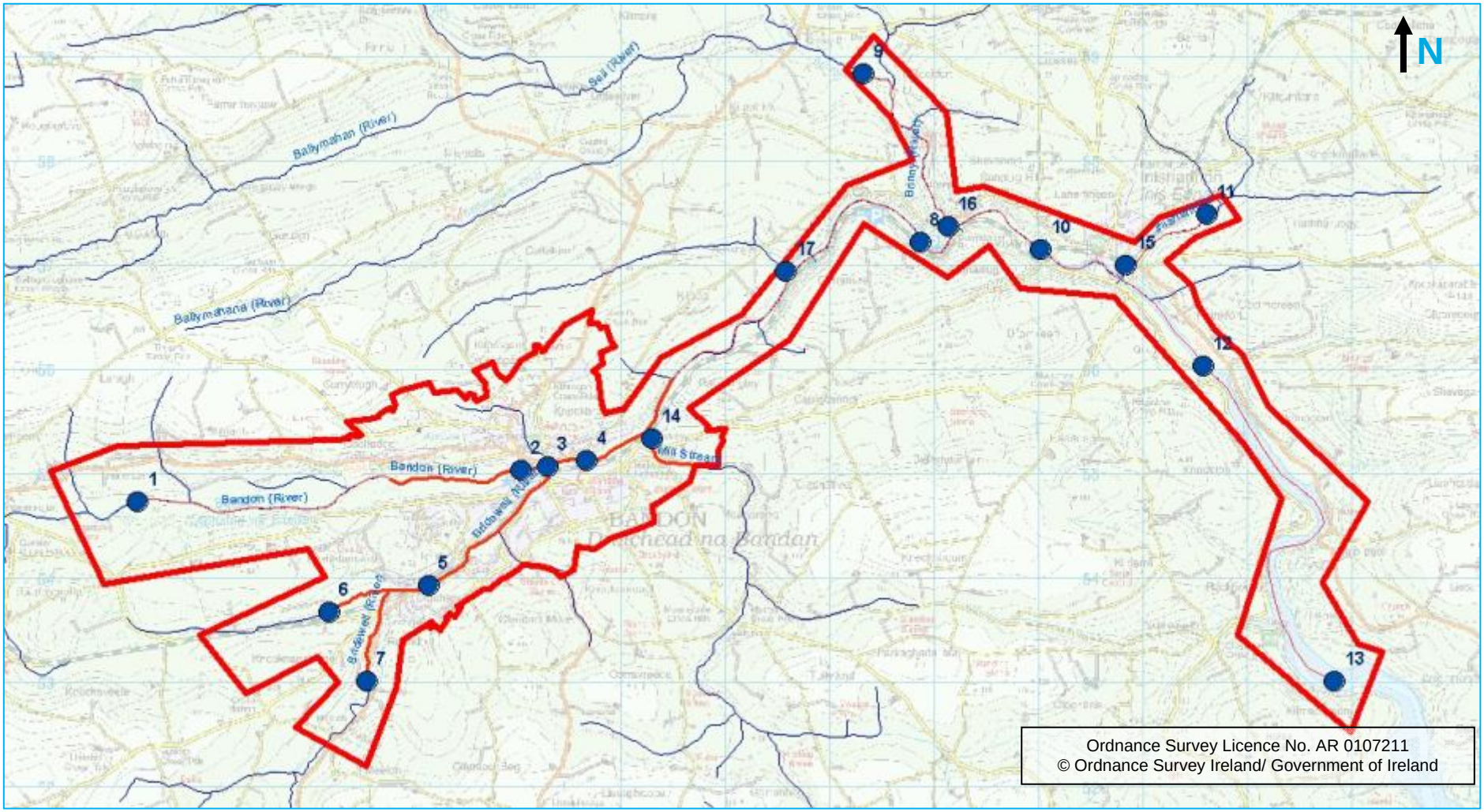
D. Hydrologic Parameter Summary

D.1 Catchment

Parameter	HEP01	HEP02	HEP03	HEP04	HEP05	HEP06	HEP07	HEP08	HEP09	HEP10	HEP11	HEP14	HEP15	HEP16	HEP17
Area	373.0	378.8	20.6	402.1	17.6	3.3	11.1	423.8	81.8	513.3	5.6	11.0	6.1	88.6	3.8
SAAR	1720	1714	1307	1690	1311	1322	1313	1669	1264	1598	1224	1271	1226	1262	1297

Bandon River Catchment




N
Ballymahon (River)
Sall (River)
Ballymahana (River)
Bandon (River)
Bandon (River)
Mill Stream
Bridewell River
Bridewell River
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
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FSR Statistical

D.3 Parameters

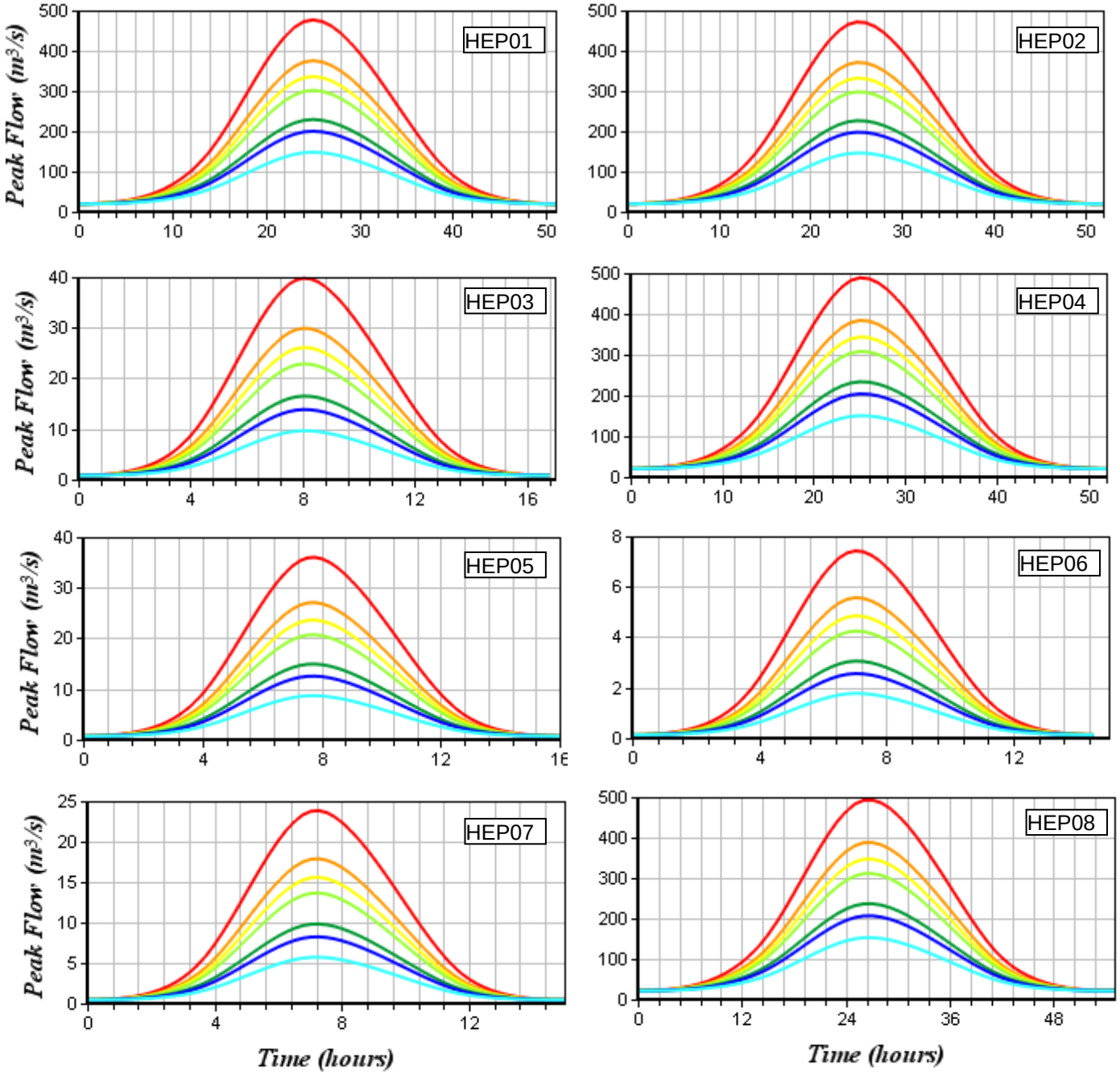
Parameter	HEP 01	HEP 02	HEP 03	HEP 04	HEP 05	HEP 06	HEP 07	HEP 08	HEP 09	HEP 10	HEP 11	HEP 14	HEP 15	HEP 16	HEP 17
URBAN	0.0033	0.0038	0.0435	0.0078	0.0132	1E-05	1E-05	0.0081	1E-05	0.0067	1E-05	0.0079	0.0354	1E-05	1E-05
MSL	49.00	52.60	7.81	53.60	6.20	2.00	4.90	58.38	14.30	59.70	2.70	7.20	3.50	16.50	4.00
M5-1Day	59.8	59	58.2	57.9	51.4	52.3	51.2	61	54.6	58.7	53	51.8	53.4	54.4	53.9
Time To Peak	9.55	9.81	3.37	9.77	3.26	2.90	3.03	10.06	5.57	10.46	2.49	3.96	2.61	6.05	3.43
Timestep	1	1	0.25	1	0.25	0.25	0.25	1	1	1	0.25	0.25	0.25	1	0.25
Storm Duration	27	27	8.25	27	7.75	7.25	7.25	29	13	29	5.75	9.25	6.25	15	8.25
ARF	0.92	0.92	0.95	0.92	0.95	0.97	0.96	0.92	0.93	0.92	0.96	0.96	0.96	0.94	0.97
SMDBAR	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5
RSMD	50.68	49.93	50.79	48.83	44.38	46.30	44.49	51.75	46.43	49.36	46.51	45.27	46.91	46.35	47.86
S1085	0.827	0.82	0.485	0.798	0.513	0.302	0.723	0.783	0.281	0.699	0.532	0.634	0.495	0.305	0.529
Stream Slope	2.16	2.10	16.95	2.14	19.31	13.55	22.29	2.12	7.94	2.07	30.11	13.02	24.56	6.84	13.55
LAKE	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
WRAP 1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
WRAP 2	0.39	0.39	1	0.43	1	1	1	0.46	1	0.55	1	1	1	1	1
WRAP 3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
WRAP 4	0.44	0.44	0	0.41	0	0	0	0.39	0	0.32	0	0	0	0	0
WRAP 5	0.17	0.17	0	0.16	0	0	0	0.15	0	0.13	0	0	0	0	0
SOIL	0.4	0.4	0.3	0.3935	0.3	0.3	0.3	0.3885	0.3	0.374	0.3	0.3	0.3	0.3	0.3
QBAR (m^3/s)	89.75	89.13	5.39	90.58	3.95	0.69	2.81	98.86	12.65	103.70	1.51	2.57	1.65	13.60	0.94

FSR Rainfall Runoff

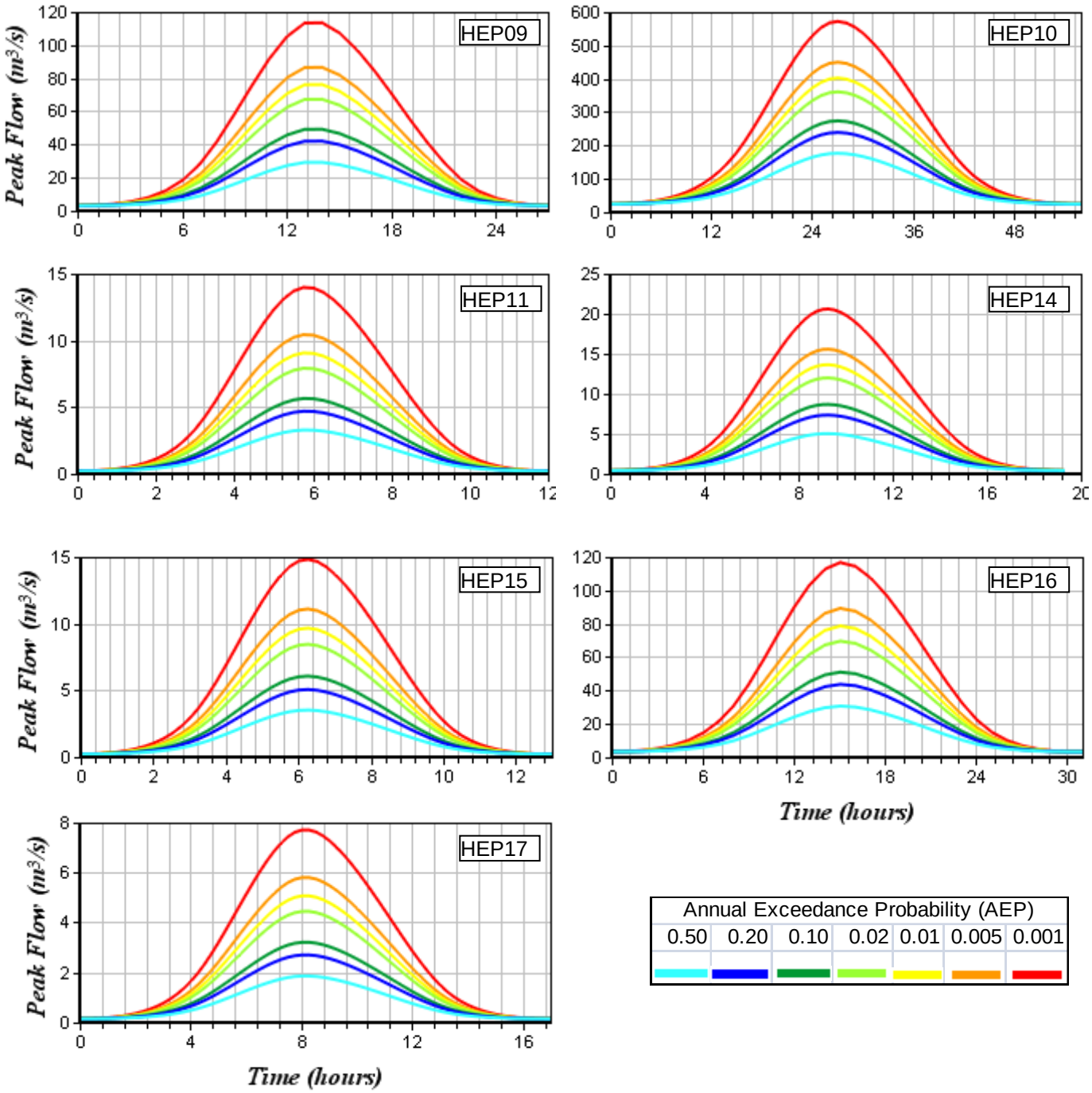
D.4 Parameters

Parameter	HEP01	HEP02	HEP03	HEP04	HEP05	HEP06	HEP07	HEP08	HEP09	HEP10	HEP11	HEP14	HEP15	HEP16	HEP17
S1085	2.16	2.10	16.95	2.14	19.31	13.55	22.29	2.12	7.94	2.07	30.11	13.02	24.56	6.84	13.55
URBAN	0.0033	0.0038	0.0435	0.0078	0.0132	1E-05	1E-05	0.0081	1E-05	0.0067	1E-05	0.0079	0.0354	1E-05	1E-05
MSL	49.00	52.60	7.81	53.60	6.20	2.00	4.90	58.38	14.30	59.70	2.70	7.20	3.50	16.50	4.00
M5-2day	83.00	81.80	80.20	80.50	81.00	81.00	81.00	80.00	81.00	81.00	81.50	82.00	82.00	81.00	81.50
r	0.214	0.219	0.225	0.226	0.248	0.247	0.248	0.213	0.245	0.218	0.25	0.25	0.25	0.242	0.25
CWI	124.77	124.75	123.82	124.70	123.83	123.85	123.83	124.65	123.72	124.49	123.63	123.74	123.63	123.72	123.80
WRAP 1	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
WRAP 2	0.39	0.39	1.00	0.43	1.00	1.00	1.00	0.46	1.00	0.55	1.00	1.00	1.00	1.00	1.00
WRAP 3	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
WRAP 4	0.44	0.44	0.00	0.41	0.00	0.00	0.00	0.39	0.00	0.32	0.00	0.00	0.00	0.00	0.00
WRAP 5	0.17	0.17	0.00	0.16	0.00	0.00	0.00	0.15	0.00	0.13	0.00	0.00	0.00	0.00	0.00
Tp	9.56	9.80	3.37	9.77	3.27	2.90	3.03	10.06	5.57	10.46	2.49	3.96	2.61	6.05	3.43
Timestep	1	1	0.25	1	0.25	0.25	0.25	1	1	1	0.25	0.25	0.25	1	0.25
SPR	41.39	41.39	30.00	40.65	30.00	30.00	30.00	40.08	30.00	38.43	30.00	30.00	30.00	30.00	30.00
Baseflow	19.24	19.47	0.80	20.37	0.69	0.13	0.43	21.20	3.07	24.55	0.21	0.42	0.22	3.32	0.15
StormDuration	27.00	27.00	8.25	27.00	7.75	7.25	7.25	29.00	13.00	29.00	5.75	9.25	6.25	15.00	8.25
Profile	Winter	Winter	Winter	Winter	Winter	Winter	Winter	Winter	Winter	Winter	Winter	Winter	Winter	Winter	Winter
ARF	0.923	0.92	0.95	0.92	0.95	0.97	0.96	0.92	0.93	0.92	0.96	0.96	0.96	0.94	0.97

D.5 FSR Rainfall Runoff Method Hydrographs



Annual Exceedance Probability (AEP)						
0.50	0.20	0.10	0.02	0.01	0.005	0.001


HEP09
HEP10
HEP11
HEP14
HEP15
HEP16
HEP17
Peak Flow (m³/s)
Time (hours)
Annual Exceedance Probability (AEP)
0.50
0.20
0.10
0.02
0.01
0.005
0.001

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