UoM 25/26 Flood Forecasting Systems (FFS)

Final Report

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Glossary

AEP	Annual Exceedance Probability (expressed as a percentage [e.g. 1%] or as a fraction of 1 [e.g. 1 in 100])
AFA	Area for Further Assessment
AFRR	Area for Flood Risk Review (also known as a Possible AFA)
APSR	Area of Potential Significant Risk (also known as AFA)
CAR	Community at Risk (also known as Probable AFA)
CFRAM	Catchment Flood Risk Assessment and Management Study
EFAS	European Flood Awareness System
FFS	Flood Forecasting System
HA	Hydrometric Area
IRR	Individual Risk Receptor
OPW	Office of Public Works
RBD	River Basin District
UoM	Unit of Management

Executive summary

The Office of Public Works (OPW) has requested a study on the possible development of a Flood Forecasting System (FFS) for Unit of Management (UoM) 25/26 which forms part of the Shannon River Basin District (RBD). OPW has identified areas that have a significant risk of flooding, originally referred to as Areas of Potential Significant Risk (APSRs), and the riparian area of the Shannon Callows. The objective of this study has been to define a flood forecasting system that is flexible to a range of needs. On the one extreme there are major floods spanning several days, which have occurred on a number of occasions over the past 40-50 years as a result of prolonged rainy periods. On the other hand, there is the incidence of localised floods, which can result from frequent and scattered rainfall events.

The report examines the distribution of the APSRs within UoM 25/26 and their source of flood risk, using OPW “Floodmaps” data. The relationship of the existing hydrometric network to the APSRs is examined to identify raingauges and river gauges that might be suitable for a localised flood forecasting system. The hydrometric network has also been considered for the potential of developing catchment scale flood forecasting modelling.

Detailed analysis of three major flood events (December 1999, August-September 2008 and November 2009) was carried out to establish catchment wetness, meteorological conditions, rainfall distribution and flood response. These serious events caused widespread and disruptive flooding, as well as affecting many of the APSRs. Some of the localised floods affecting APSRs, which were mostly caused by heavy summer rainstorms, have also been analysed. The results from these analyses are used in the second part of the report to define what may and may not be feasible for an effective flood forecasting system.

Very little exists at present in terms of formalised flood forecasting in UoM 25/26, and severe weather forecasts and warnings issued by Met Éireann in relation to rainfall are generalised. The report provides a detailed examination of the facilities and capacities required to operate a real-time localised flood forecasting service.

It is suggested that a two-tier system of flood forecasting could operate effectively. The primary system would operate on a catchment basis with direct communication (telemetry) from 15 raingauges and 18 river gauges. Except for one new river gauge, all these instruments would operate from existing measurement stations operated by OPW, Met Éireann and Local Authorities. A secondary system, located in more direct proximity to APSRs would require the automation of 8 raingauges from existing sites and 12 river gauges. One additional raingauge and up to 4 river gauges would be required.

A range of regular information and data feeds, on a daily or sub-daily basis have been suggested as a means of supplying direct information or as data feeds into a modelling system. Some approximate preliminary cost estimates have been provided, but it is emphasised that a more detailed plan for the observation, communications and modelling provisions would have to be made before the full cost of a system could be estimated. Costs and inputs would also need to be compared with benefits that might accrue from a forecasting system. Some suggestions have also been made with regard to the type of warnings that might be linked to the forecasting system.

1 Appreciation of the Areas of Potential Significant Risk

1.1 Statement of Problem

The basic requirement of the fluvial flood forecasting system (FFS) is to provide timely and relevant information on flood occurrence in relation to a range of impacts. The information given needs to meet requirements for preparedness and response, which are appropriate and effective. This report aims to address flooding problems over the fluvial Shannon catchments – the Shannon Upper and Lower Unit of Management (UoM 25/26), and covers a range of locations and types of fluvial flooding. UoM 25/26 combines in one Unit of Management the two hydrometric areas HA25 (Shannon Lower) and HA26 (Shannon Upper). The foci of interest for the FFS are the Areas of Potential Significant Risk (APSRs). For the draft version of this report the APSRs considered are the Communities at Risk (CARs) and the Individual Risk Receptors (IRRs). A subsequent revision of this report may need to be produced at Preliminary Options Reporting Stage and would consider additional APSRs arising as a result of the Flood Risk Review process which is considering the Areas for Flood Risk Review (AFRR).

Following submission of the draft version of this flood forecasting report Jacobs was informed of changes to the naming of Areas of Potential Significant Risk (APSRs), Communities at Risk (CARs) and Areas for Flood Risk Review (AFRR). APSRs will now be known as Areas for Further Assessment (AFA), CARs as Probable AFAs and AFRRs as Possible AFAs. This report continues to use the old names to avoid significant reworking of the figures and tables and to minimise inconsistencies with the Inception Reports.

The APSRs comprise a range of locations and catchment types. In terms of flood risk types, there is a primary differentiation between localised events, and those of a general and widespread nature. The more widespread floods may produce a range of impacts, e.g. riparian agricultural flooding, inundation of urban areas, disruption of transport.

The geography of the River Shannon, with its considerable variations in geology and geomorphology, brings its own peculiarities to the flood forecasting problem. It is the longest river in Ireland and Britain, and although much smaller than major rivers on the European scale, e.g. the Rhine, Loire, Rhone, etc., it is included in the European Flood Awareness System (EFAS) set of catchments, as the total catchment area is greater than 4,000 km^2. This system is in a developmental phase for the Shannon, and would in any case operate on a catchment-wide scale, rather than for localised foci. The Shannon catchment is developed in a largely lowland area with complex drainage patterns containing many tributaries and lakes. The low water surface slopes, long channel lengths in relation to area, and significant storage (some controlled), results in floods on the main river, and most of the major tributaries, that develop and decline slowly, and are of considerable volume. The catchment experiences a generally wet climate throughout the year, with annual average rainfall generally in the range 900–1,200 mm, with frequent rainfall events, particularly in the winter months.

The problem therefore is to define a flood forecasting system that is flexible to a range of needs. On the one extreme there are major floods spanning several days, which have occurred on a number of occasions over the past 40–50 years in response to prolonged rainy periods. On the other hand, there is the incidence of

localised floods, which can result from frequent and more scattered rainfall events, exacerbated by problems stemming from local drainage provision.

1.2 Distribution and nature of the APSRs

Most APSRs are localised sites in small towns or parts of larger towns and cities. Some are located on large or major rivers with a history of flooding, e.g. places along the River Shannon, which may therefore be considered primarily a fluvial flooding problem associated with major events. Some ASPR sites are associated with smaller rivers, where floods may be of a more flashy nature, and where the rainfall (pluvial) component is also contributory. Some other sites appear to be flooded as a result of rainfall over a prolonged period, and in these cases land drainage is sometimes a causative issue. The location of the preliminary APSRs is shown on Figure 1.1 and the summary of principal causes and nature of flooding are given in Table 1-A. It should be noted that the list of APSRs is not definitive and may be subject to change in a later stage of the CFRAM study.

The implication of the range of causes and impacts from the standpoint of flood forecasting and warning is that no single approach would be appropriate. Thus different means of identifying impending flood conditions on a catchment-wide scale, as well as conditions likely to affect specific locations, have to be considered. There are five locations at which the OPW "Floodmaps" database does not hold any details of past flooding, as indicated in the last column of Table 1-A.

Table 1-A Summary of flood types at CARs and IRRs in UoM 25/26

<table>
<tr><th colspan="2">Location</th><th rowspan="2">County</th><th rowspan="2">River</th><th rowspan="2">Nature of flooding impact*</th></tr>
<tr><th>Ref no</th><th>Name</th></tr>
<tr><td>CAR02</td><td>Abbeyshrule</td><td>Longford</td><td>Glen Lough, Black River</td><td>No data available</td></tr>
<tr><td>CAR06</td><td>Athlone</td><td>Westmeath</td><td>Shannon</td><td>Fluvial: widespread and recurrent</td></tr>
<tr><td>CAR07</td><td>Ballaghaderreen</td><td>Roscommon</td><td>Lung</td><td>Pluvial: localised - sewer network unable to cope with runoff</td></tr>
<tr><td>CAR08</td><td>Ballinasloe</td><td>Galway</td><td>Suck</td><td>Fluvial: widespread and recurrent</td></tr>
<tr><td>CAR11</td><td>Birr</td><td>Offaly</td><td>Little Brosna</td><td>Pluvial: prolonged heavy rainfall</td></tr>
<tr><td>CAR12</td><td>Borrisokane</td><td>Tipperary</td><td>Ballyfinboy</td><td>No data available</td></tr>
<tr><td>CAR13</td><td>Boyle</td><td>Roscommon</td><td>Boyle</td><td>Fluvial: widespread and recurrent</td></tr>
<tr><td>CAR15</td><td>Cappamore</td><td>Limerick</td><td>Bilboa</td><td>Fluvial</td></tr>
<tr><td>CAR16</td><td>Carrick on Shannon</td><td>Leitrim</td><td>Shannon</td><td>Fluvial: widespread and recurrent</td></tr>
<tr><td>CAR18</td><td>Castleconnell</td><td>Limerick</td><td>Shannon</td><td>Fluvial: widespread and recurrent</td></tr>
<tr><td>CAR19</td><td>Castlerea</td><td>Roscommon</td><td>Suck</td><td>Fluvial: localised</td></tr>
<tr><td>CAR21</td><td>Clara</td><td>Offaly</td><td>Brosna</td><td>Fluvial and pluvial</td></tr>
<tr><td>CAR23</td><td>Clonaslee</td><td>Laois</td><td>Clodiagh</td><td>No data available</td></tr>
<tr><td>CAR26</td><td>Drumshanbo</td><td>Leitrim</td><td>Shannon</td><td>Fluvial: widespread and recurrent</td></tr>
<tr><td>CAR27</td><td>Edgeworthstown</td><td>Longford</td><td>Glen Lough, Black River</td><td>No data available</td></tr>
<tr><td>CAR30</td><td>Kilbeggan</td><td>Westmeath</td><td>Brosna</td><td>Pluvial and fluvial - sewer network unable to cope with runoff</td></tr>
<tr><td>CAR31</td><td>Kilcormac</td><td>Offaly</td><td>Silver River</td><td>Pluvial: saturated catchment & land drainage problems</td></tr>
</table>

Location				
CAR34	Killaloe	Tipperary	Shannon	Fluvial: widespread and recurrent
CAR37	Limerick City	Limerick	Shannon	Fluvial and tidal; also affected by surge and strong winds
CAR40	Longford	Longford	Camlin	Fluvial local effects of widespread floods
CAR41	Mohill	Leitrim	Lurge (Rhinn)	Pluvial and fluvial with saturated catchment
CAR42	Mullingar	Westmeath	Brosna	Pluvial and fluvial with saturated catchment
CAR43	Nenagh	Tipperary	Nenagh	Fluvial
CAR45	Newport	Tipperary	Newport	Pluvial and fluvial
CAR46	O'Briensbridge	Limerick	Cloonlara	Fluvial: widespread and recurrent
CAR47	Pollagh	Offaly	Brosna	Localised fluvial
CAR48	Portumna	Galway	Shannon	Fluvial: widespread and recurrent
CAR49	Rahan	Offaly	Clodiagh	Pluvial: prolonged heavy rainfall
CAR51	Roscommon	Roscommon	Hind	Pluvial: saturated catchment & land drainage problems
CAR52	Roscrea	Tipperary	Bonnow	*No data available*
CAR54	Shannon Harbour	Offaly	Shannon	Fluvial: widespread and recurrent
CAR57	Cloonlara	Clare	Cloonlara	Fluvial: widespread and recurrent
IRR2	Lumcloon P.S.	Offaly	Brosna	Fluvial: widespread and recurrent
IRR3	Durrow Heritage Site	Offaly	Brosna	Fluvial
IRR4	Shannonbridge P.S.	Offaly	Shannon	Fluvial: widespread and recurrent
IRR5	Lanesborough P.S.	Longford	Upper Shannon	Fluvial: widespread and recurrent
-	Shannon Callows	Westmeath, Roscommon, Galway, Offaly, Tipperary	Shannon, Suck	Fluvial: widespread and recurrent

* Information on flooding is taken from the “Floodmaps” pages on the OPW website.

1.3 The hydro-meteorological network in relation to APSRs

The review of flood events at APSRs has shown that whereas most are affected during the major catchment-wide floods, the forecasting of local conditions would be important for giving an early warning of localised events. The flood risk at APSRs may be thought of as “hot-spots”, where local flood protection or mitigation measures could be related to triggers at local hydro-meteorological stations. CARs and IRRs, forming the (preliminary) APSRs considered in this report, are plotted in Figure 1.1 and the CARs summarised in Table 1-B. As stated in Section 1.2 the list of APSRs is preliminary at the time of preparing this report. The hydro-meteorological networks are shown in Figures 1.2 and 1.3.

Table 1-B APSRs and hydro-meteorological stations

No.	APSR NAME	RAIN-GAUGE No	LOCATION	RIVER GAUGE No	LOCATION
2	Abbeyshrule	2130	Rathowen, Killinagh	26306	Glen Lough Upper
6	Athlone	1929	Athlone OPW	26027	Athlone
		4629	Athlone Glynwood	26088	Hodson's Bay
7	Ballaghaderreen	1128	Loughglinn	26014	Banada Br
8	Ballinasloe	2628	Ballinasloe, Derrymullen	26007	Bellagill
		2828	Ballinasloe, Pollboy Lock	26005	Derrycahill
11	Birr			25021	Croghan
		1475	Gurteen	25022	Syngefield
12	Borrisokane			25025	Ballyhooney
		1475	Gurteen	25132	Borrisokane
13	Boyle	7329	Boyle, Low Park	26012	Tinacarra
		5229	Boyle, Marian Rd	26108	Boyle Abbey Br
15	Cappamore	6719	Limerick Junc. (Solo Head)	25004	New Bridge
16	Carrick on Shannon	1529	Drumsna, Albert Lock	26324	Carrick on Shannon
18	Castleconnell	1619	Birdhill, Parteen Weir		
19	Castlerea	1128	Loughglinn	26006	Willsbrook
21	Clara			25035	Clara
		3522	Horseleap	25046	Lismoyny
23	Clonaslee			25301	Bracknagh Br
		3422	Geashill	25203	Curraghnadeige
26	Drumshanbo	1729	Drumshanbo	26109	Drumshanbo
27	Edgesworthtown			26323	Edgeworthstown
		2130	Rathowen, Killinagh	26141	Lisnagrish
30	Kilbeggan	3522	Horseleap	25013	Newell's Br
		3022	Tyrrellspass	25124	Ballynagore
31	Kilcormac			25014	Millbrook
		3422	Geashill	25220	Ballyboy
34	Killaloe	6019	Killaloe Locks		
37	Limerick City			25001	Mulkear
				25075	Shannon
40	Longford			26019	Mullagh
		6829	Termonbarry	26222	Longford
41	Mohill	1829	Dromod (Ruskey)		
		1529	Drumsna, Albert Lock	26042	Mohill
42	Mullingar	875	Mullingar		
		1675	Mullingar_CR300X	25050	Mullingar Pump Hse.
43	Nenagh			25027	Gourdeen
				25029	Clarianne
		5819	Nenagh, Connolly Park	25038	Tyone
45	Newport			25308	Waterpark Bridge
		6919	Newport, Coole	25054	Rockvale
46	O'Briensbridge	1619	Birdhill, Parteen Weir	25075	Parteen Weir
47	Pollagh	3522	Horseleap	25015	Pollagh

No.	APSR NAME	RAIN-GAUGE No	LOCATION	RIVER GAUGE No	LOCATION
48	Portumna			25051	Portumna
				25056	Meelick Weir u/s
		1819	Portumna OPW	25058	Victoria Lock
49	Rahan	3522	Horseleap	25016	Rahan
51	Roscommon	5829	Roscommon, Voc Sch	26016	Ballymurray
52	Roscrea			25040	Roscrea
		6119	Roscrea, New Road	25111	Clybanane
54	Shannon Harbour			25011	Moystown
		1719	Banagher Canal HSE	25017	Banagher
57	Cloonlara	1619	Birdhill, Parteen Weir	25075	Parteen Weir

1.3.1 Hydrometric stations

As fluvial flooding is by far the most common cause of flooding at APSRs, it has been assumed that irrespective of the precise causes of historic flooding, observations from the nearest river gauge would be a useful indicator of flood risk. Of the 32 APSRs, only two, Castleconnell and Killaloe, do not have a hydrometric station within the immediate locality or catchment in which the APSR is situated.

We understand that the majority of the stations listed against APSR sites in Table 1-B are operated by the OPW Hydrometric Section and are thus equipped with data loggers. In order to be used for flood warning purposes, any digital data needs to be transmitted in near real time by some form of automatic interrogation into a dedicated database. It is understood that there are already plans for such a system which will provide a web-based presentation of data.

1.3.2 Rainfall station network in relation to APSRs

An open daily raingauge can be identified in reasonable proximity (10-15 km) of all APSRs. (Although no raingauges are identified against CAR 37 Limerick, Met Éireann raingauges are located nearby in adjacent units of management). Although the immediate relationship between rainfall at a particular gauge and the occurrence of flooding cannot be assumed, warning of heavy rainfall, either as intensity or accumulation could provide a useful alerting system. Suitable trigger or threshold quantities that cause flooding would need to be identified, and for useful observations to be made, daily raingauges would need to be replaced or supplemented by sub-daily (tipping-bucket) recording raingauges connected by telemetry. Those sites where a pluvial component has been noted as a cause of flooding would particularly benefit from rainfall telemetry, and might require alerting thresholds for observed intensities. Table 1-A indicates that pluvial components are possible flood contributory causes at nine APSR locations.

The OPW already has telemetry raingauge networks operating in the Suir and Blackwater catchments, to provide inputs into flood forecasting models. These networks include a total of 64 raingauges, giving a very dense network. One of the reasons for the dense networks is that the primary requirement for the forecasting systems in these catchments is to allow adequate time for erecting demountable defences, which requires a high level of accuracy in predicted levels. In large rivers such as the river Shannon the development of floods and their propagation downstream are largely dependent on the river network and its hydraulics, and less responsive to localised rainfall. Therefore its raingauge network (and flood forecast

model units) can be less dense. Although the tributaries and upper reaches of the Shannon require a denser network, they may still not require the same raingauge network density as the Suir and Blackwater catchments if demountable defences are not envisaged.

An alerting system for APSRs could concentrate on automatically triggered alarms from rainfall accumulation and/or intensity exceedence thresholds, which would be less demanding than the regular polling required to support models.

1.4 Principal causes and impacts of flooding

1.4.1 Major flooding events

A review of the annual maximum (Amax) flood series (level and flow) provided by the OPW, covering the period since the early 1950s, identified several major events which were widespread in their occurrence across the catchment. Information from OPW's Floodsmaps.ie website shows that floods of a greater or lesser degree are common throughout the Shannon Upper and Lower UoM in each winter, and that some floods have occurred in summer months. To ensure the maximum coverage of river flow and rainfall data, and to maximise the use of the electronically available archive of synoptic weather maps, it was decided to analyse major events which occurred within the last 15 years. These events are also likely to have the best availability of local flood data and flood reports.

A group of stations were selected to study 3 major events. These were arranged so as to represent all major tributaries and headwaters of Unit of Management 25/26, and to ensure that the event affected the whole of the catchment. The stations used and the period covered by the flood events are listed in Table 1-C. Locations are shown in Figure 1.2.

Table 1-C Catchments used in analysis of major flood events

Station No	Station Name	River	Catchment area (km^2)	Annual Average Rainfall (mm)	Data coverage (15 min)		
					1/10/09-30/11/09	1/8/08-30/9/08	2/11/99-30/1/00
25001	Annacotty	Mulkear	647.6	1,165	Yes	Yes	Yes
25006	Ferbane	Brosna	1,162.8	936	Yes	Data missing 22/8-2/9	Yes
25016	Rahan	Clodiagh	253.8	949	Yes	Yes	Yes
25021	Crohgan	Little Brosna	479.2	928	Yes	Yes	Yes
26006	Willsbrook	Suck	184.8	1,120	Yes	Yes	No data
26007	Bellagill	Suck	1,207.2	1,045	Yes	Yes	Yes
26008	Johnston's Bridge	Rinn	280.6	1,035	Yes	Yes	Yes
26012	Tinacarra	Boyle	519.9	1,143	Yes	Yes	Yes
26019	Millagh	Camlin	253.0	979	Yes	Yes	Yes
26021	Ballymahon	Inny	1,098.8	945	Data missing 24/10-18/11	Yes	No data

The main characteristics of the chosen events can be summarised as follows.

October - November 2009
This is widely understood to be the worst flood since major floods in 1954 and 1925, and may possibly have exceeded these events in terms of overall impact. Like most winter floods on the Shannon, the peak developed over a period of weeks, following the onset of wet weather in October, and affected more parts of the river system than other major floods in December 2006-January 2007 and December 2007-January 2008. The causative rainfall for these floods has been reported in detail by Met Éireann[1].

August - September 2008
Localised floods may occur during any summer, but generalised flooding is rare. Large scale summer floods are infrequent and maybe of a smaller magnitude than winter events, and can cause considerable disruption, especially to the agricultural and tourist sectors. Much of central and eastern Ireland was affected by a major rainfall event in August 2008, and in general this was a very wet summer[2]. Eight river stations in the Shannon Lower subcatchment (hydrometric area 25), and three in the Shannon Upper subcatchment (hydrometric area 26) recorded the annual maximum flow for water year 2007-08 during August 2008. Slow moving summer depressions are a feature of the climate of the southern half of Ireland, and one of these, the remnants of Hurricane Charlie in August 1986, caused serious flooding in parts of Co. Wicklow and Co Dublin[3].

December 1999 - January 2000
Although not achieving the widespread extent or magnitude of flood peaks as those in the flood of 2009, OPW have suggested that this flood should be investigated as it is considered that this event was the most severe since the major flood of 1954. Peaks at many gauging stations during the 1999-2000 winter event exceeded those that occurred in 2006-07 and 2007-08, which both also produced large floods.

The 3 events show the following common features, illustrated in Table 1-D:

- An initial significant flood event;
- A period of a number of consecutive events (4 or more) over a period of a 1-2 weeks, with increasing peaks or maintaining higher levels as catchment response increases; and
- A period of sustained high flow, during which 1 or more major peaks occur.

[1] Report on the Rainfall of November 2009, S Walsh, Climate Note No. 12, Met Éireann, Feb 2010
[2] 2008 Summer Rainfall in Ireland, P Lennon & S Walsh. Climate Note No. 11, Met Éireann, December 2008
[3] Storm of $25^{th}/26^{th}$ August 1986 which caused flooding in the Dargle catchment (Bray) and Dodder catchment (Dublin). G O Kelly, Meteorological Service, Dublin, 1986

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Table 1-D Summary of flood peaks in major events (Date of peak and maximum flow, m^3/s)

Table 1-D (i) Flood peaks for October - November 2009 event

Station No	Date of initial peak	Initial peak max. flow, m^3/s	Date of main peak	Main peak max. flow, m^3/s
25001	22/10	27.65	25/11	125.5
25006	23/10	17.91	21/11	109.4
25016	23/10	7.52	20/11	28.89
25021	22/10	10.99	24/11	34.18
26006	21/10	3.88	20/11	64.93
26007	24/10	16.81	22/11	221.5
26008	23/10	2.93	21/11	40.07
26012	25/10	6.03	24/11	108.8
26019	23/10	3.99	21/11	48.34
26021	23/10	17.80	20/11	119.2

Table 1-D (ii) Flood peaks for August - September 2008 event

Station No	Date of initial peak	Initial peak max. flow, m^3/s	Date of main peak	Main peak max. flow, m^3/s
25001	1/8	56.97	6/9	114.7
25006	2/8	15.33	19/8	94.95
25016	1/8	7.70	18/8	31.80
25021	1/8	15.12	17/8	33.69
26006	3/8	7.82	18/8	33.36
26007	No data	-	[1] 17/9	74.36
26008	3/8	1.20	18/8	15.57
26012	No peak	-	[2] 17/9	39.04
26019	3/8	3.35	18/8	14.80
26021	3/8	7.86	17/8	51.93

[1] Peak flow on 22/8, 66.71 m^3/s

[2] Peak flow on 20/8, 28.83 m^3/s

Table 1-D (iii) Flood peaks for December 1999 - January 2000 event

Station No	Date of initial peak	Initial peak max. flow, m^3/s	Date of main peak	Main peak max. flow, m^3/s
25001	5/11	108.8	25/12	113.4
25006	6/11	68.54	26/12	91.13
25016	5/11	19.63	25/12	27.08
25021	5/11	26.69	25/12	32.53
26006	No data	-	No data	-
26007	8/11	51.21	27/12	123.1
26008	6/11	11.68	26/12	29.34
26012	9/11	18.25	27/12	60.63
26019	7/11	13.26	26/12	31.66
26021	No data	-	No data	-

A more detailed description of each event follows below, presenting the characteristics of the flood hydrographs, the causative rainfall (quantity and distribution), and the weather conditions that produced the rainfall.

Hydrographs which illustrate the main features of the flood in different parts of the overall catchment, are provided for each event at the following gauging stations: (refer to Figure 1.2).

- *25001: R. Annacotty at Mulkear. This is a highly responsive river in the south- eastern part of hydrometric area (HA) 25, joining the River Shannon close to Limerick;*
- *25006: R. Brosna at Ferbane. The Brosna is a major left bank tributary of the Shannon, joining the main river downstream of the Shannon-Suck confluence;*
- *26007: R. Suck at Bellagill. This station is in the downstream part of the catchment, close to Ballinasloe, and is the main right-bank tributary of the Shannon. The flood response is gradual, with individual peaks absorbed in a general rise, influenced by backwater effects from the confluence with the River Shannon, but also resulting from much of the catchment being developed on limestone; and*
- *26012: R Boyle at Tinnacarra. The Boyle is one of the main branches of the upper Shannon and drains a catchment developed mostly on limestone strata, which causes the catchment to respond in a gradual build up, similar to the Suck.*

Daily rainfall data from Met Éireann for 40 stations has been used to produce isohyetal maps of the main rainfall period leading up to the event. The spatial distribution of these stations is fairly regular, and provides a good representation of rainfall distribution and total depth. Hyetographs from eight stations listed in Table 1-E give a representation of the time distribution of rainfall different parts of the catchment. The locations of these rainfall stations are shown in Figure 1.3. Rainfall data has also been compiled for the main periods of storm activity, and for a running 5-day accumulation. It is considered that this latter statistic could be a useful indicator of flood potential.

Table 1-E Rainfall stations used to produce hyetographs for event analyses

Station No.	Station name	Location in catchment
1729	Drumshanbo	North, upper Shannon
1128	Loughglinn	NW, upper Shannon/Suck
2230	Coole	NE, Glen Lough Upper
2628	Ballinasloe	Lower Suck
1719	Banagher	Central Shannon
3022	Tyrellspass	East, upper Brosna
6119	Roscrea	SE, Little Brosna
6019	Killaloe	South, lower Shannon

Soil moisture deficit (SMD) data, estimated on a daily basis by Met Éireann at their observation stations at Gurteen, Knock Airport, Mullingar and Shannon Airport, has been obtained for the periods leading up to the flood maxima. The locations of these stations are shown in Figure 1.2. The changes in SMD are plotted for each event, and these clearly indicate when SMD is eliminated and soils exceed field capacity, assumed when SMD reaches a value of -10mm.

Graphs of all the 3 hydrological and hydro-meteorological variables for each of the three events are presented in Appendices A (November 2009), B (August-September 2008) and C (December 1999-January 2000).

JACOBS

OPW The Office of Public Works

Figure 1.1 CARs and IRRs in Unit of Management 25/26

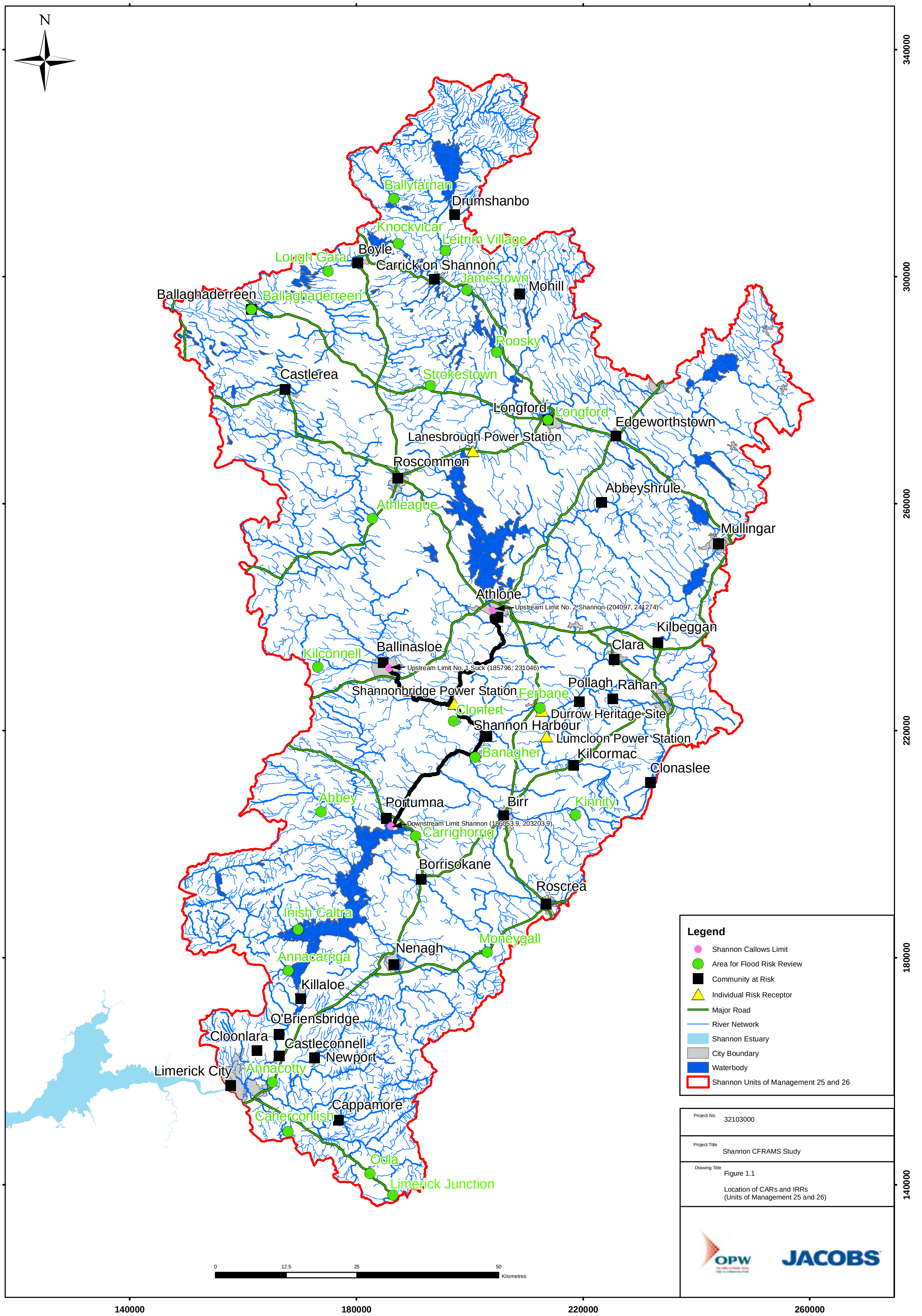


Figure 1.2 SMD and Hydrometric Stations in Unit of Management 25/26

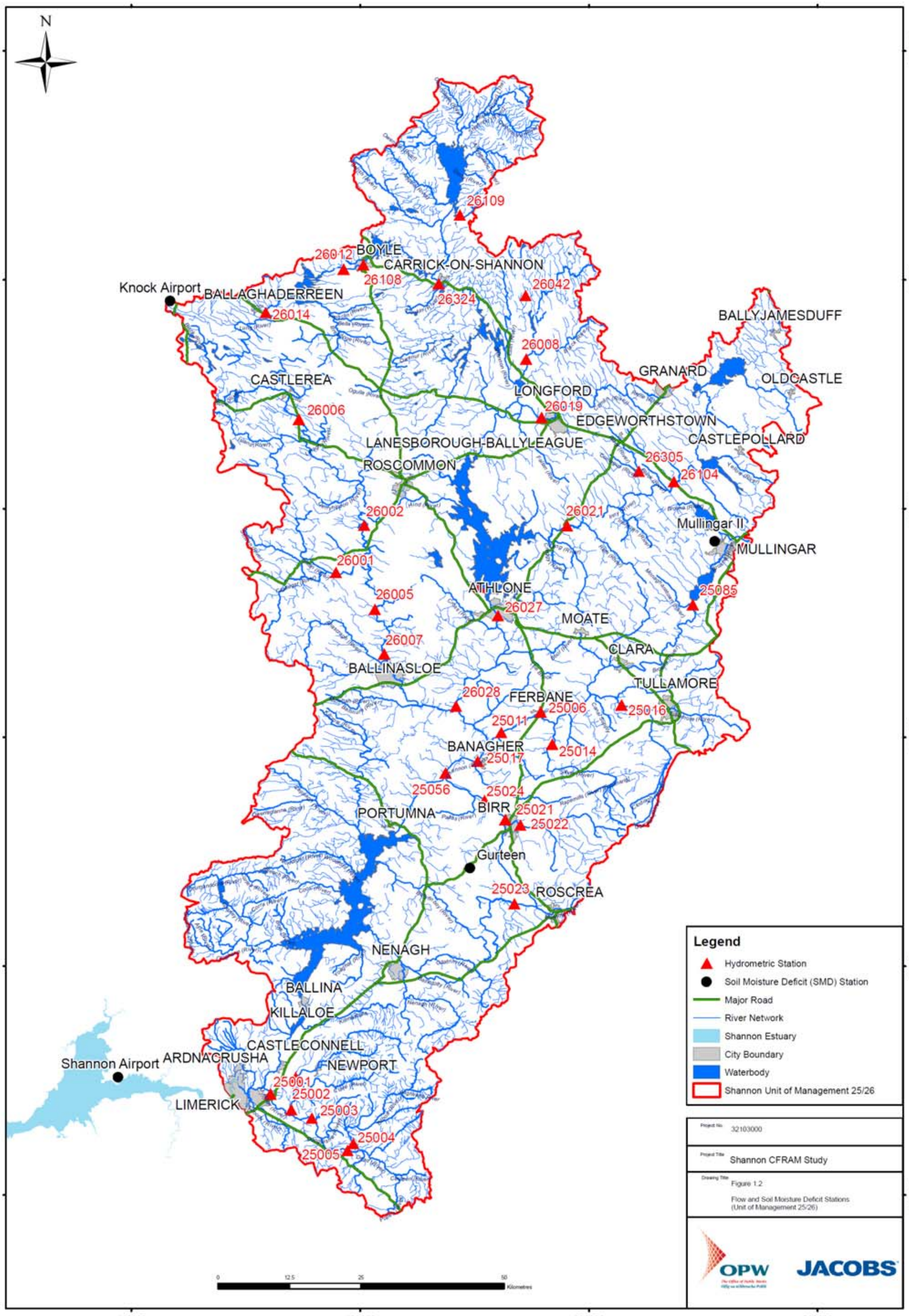
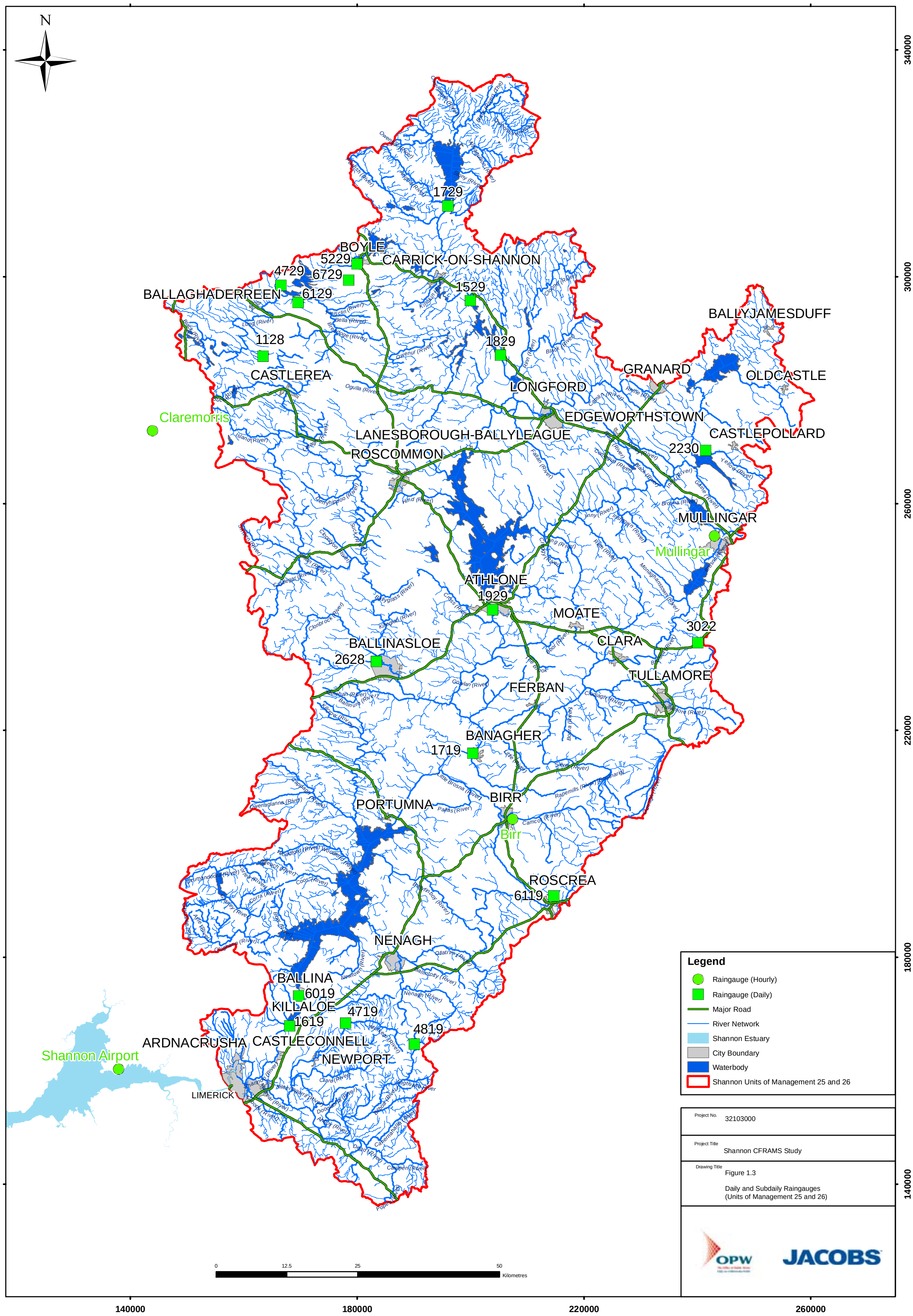


Figure 1.3 Raingauges in Unit of Management 25/26



1.4.2 October – November 2009

This event affected much of Ireland, and on the River Shannon produced record maximum levels at many locations in both the upper and lower catchments[4]. The representative hydrographs are shown in Appendix A, Figures A.1 (a–d).
The more responsive catchments (a and b) experience minor spates in the first week of October: 3 separate peaks are shown. Following further minor spates, a sharp flood peak was recorded on 1 Nov (Mulkear) and 2 Nov (Ferbane). At stations on the Suck (c) and Boyle (d), there was minimal increase in flow over this period, levels only beginning to rise more significantly after 1 November. The early November spate at stations (a) and (b) was followed by a period of frequent flood peaks, culminating in a period of persistent high flow from 21 to 25 November. The less responsive rivers show a steady rise in flow from 1 to 17 November, after which a large increase in flow takes place, reaching peak levels on 21-22 November.

The common occurrence of flood flows over the whole of the catchment suggests widespread occurrence of wet weather, and the similarity of timing of the maxima would indicate that a major, widespread rainfall occurred over an already saturated catchment. This is confirmed by SMD data, which shows that at the beginning of October some deficits existed, even in poorly drained soils – see Figures A.2 (a–d) in Appendix A. However, by 20 October all four of the observation sites reported 0mm SMD for well drained soils, and for moderately and poorly drained soils, field capacity had already been exceeded. Although Shannon Airport had the largest initial SMD, at close to 30mm, saturation of all soil types had also taken place by 20 October. Thus from 20 October the whole catchment was fully saturated.

The daily rainfall record for representative stations across the whole of UoM 25/26, Appendix A, Figures A.3 (a–h), shows that total falls ranged between 260mm to over 500mm for the two months. The two events that caused the main flood peaks are distinct, as illustrated in Figures A.3 (a–h) and summarised in Table 1-F. The records show that from mid-October through to the end of November, rain fell on almost all days, with the 5-day cumulative totals steadily increasing to a peak during the period 15 to 19 November. There were few incidences of the daily rainfall total exceeding 30mm – some of these occurrences were in the 30-31 October period and others in the days immediately preceding the flood maximum on 21-22 November.

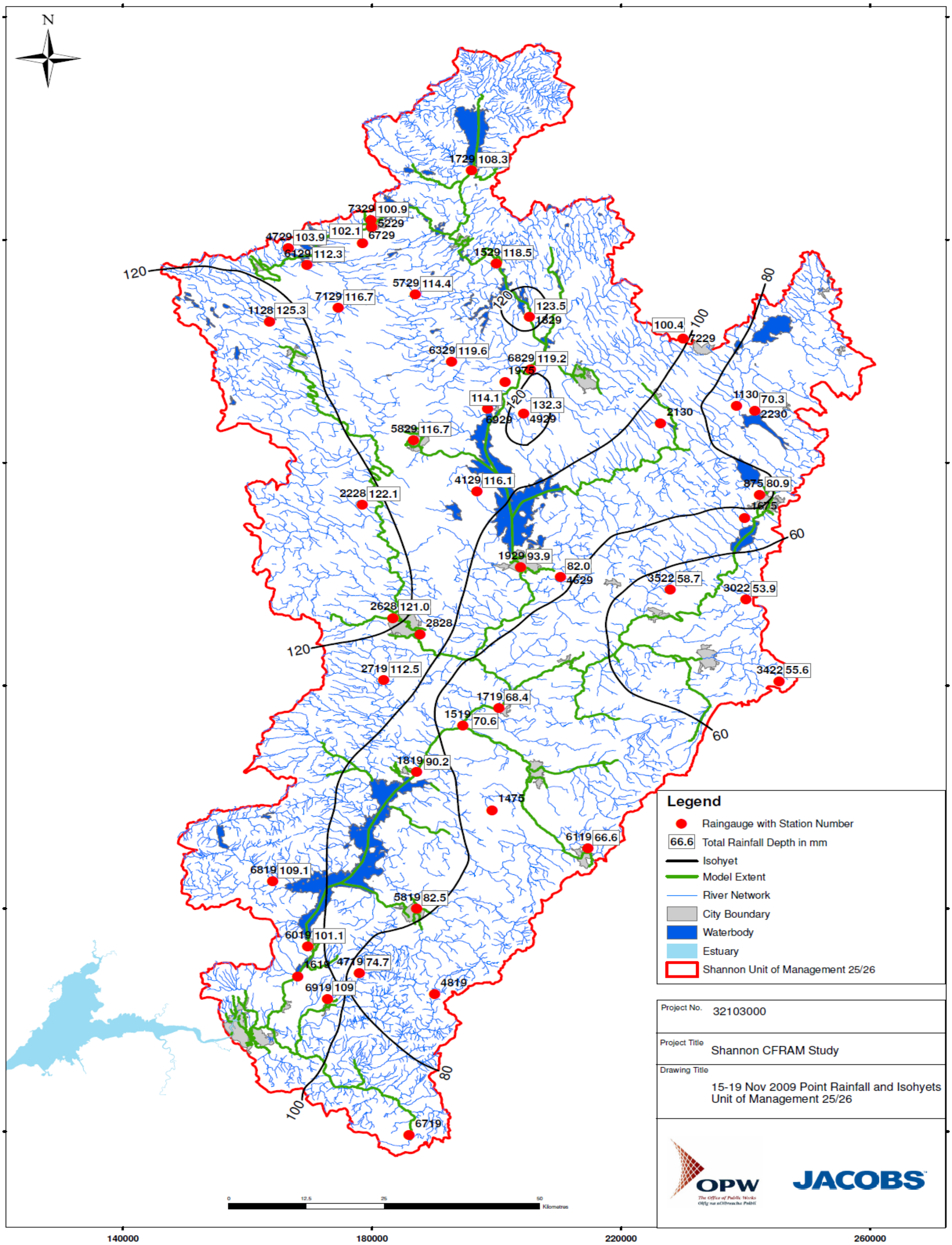
Table 1-F Summary rainfall statistics, October-November 2009

Station No	Total rainfall (mm) 1/10 – 30/11	Days with rainfall >30mm	Total 2-day rainfall (mm) 30/10 – 31/10	Total 5-day rainfall (mm) 15/11 – 19/11
1729	448.6	0	41.9	108.3
1128	416.0	2	32.6	125.3
2230	260.1	0	26.5	70.3
2628	389.6	1	34.0	121.9
1719	292.6	1	33.5	68.4
3022	295.6	1	35.9	53.9
6119	385.9	1	45.3	66.6
6019	517.5	3	51.4	101.1

[4] Flooding in November 2009 – Report by OPW Hydrometric Section

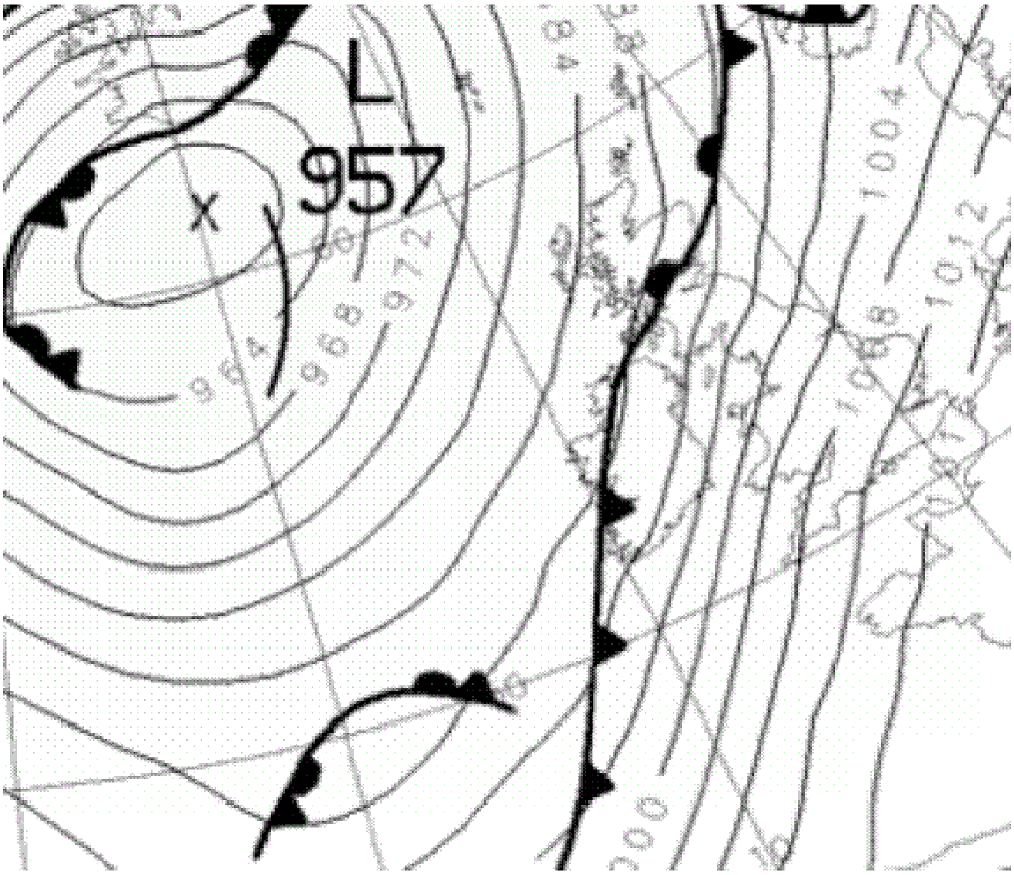
The isohyet map of the 5-day rainfall accumulation from 15-19 November is shown in Figure 1.4. This shows that the whole of the western half of the catchment received over 100mm of rain, with much of the River Suck network experiencing 120mm or more.

Figure 1.4 Isohyetal map of 5-day rainfall, 15 – 19 November 2009



Inspection of the synoptic weather charts over the two month period shows the calm weather of early October being replaced by typically changeable weather. After several rain-bearing systems in late October and early November, the prelude to continuous wet weather initiated on 15 November with a trough to the west of Ireland, with a secondary low developing to the south-west. Over the next 2-3 days, a number of fronts and minor troughs crossed Ireland, and by 17 November a “conveyor-belt” of depressions were strung-out from the coast of Newfoundland to Norway. This culminated in a prolonged period on 18-19 November, with a complex low and a near-stationary waving front lying over western Ireland. This situation is illustrated in Figure 1.5 for 12hrs on 19 November: over the next 12 hours the cold front remained more or less stationary, with waves generated along its length, producing extensive rainfall.

Figure 1.5 Synoptic weather chart, 12hrs 19 November 2009



1.4.3 August – September 2008

Although not uncommon, summer floods are normally associated with localised, heavy downpours over small areas. The occurrence of major flooding affecting wide areas in summer is quite unusual however, and this event is included as an example. Flooding occurred over much of the southern and eastern parts of Ireland, and the Shannon as a whole was affected (see Lennon and Walsh)[2].

Two main periods of flooding occurred. The first took place between 10 and 20 August and the second from 5 September, through to the middle of that month. The representative hydrographs in Appendix B, Figures B.1 (a–d) illustrate this pattern, with frequent distinct, sharp peaks in the responsive catchments, and two periods of gradually increasing high flows in catchments with large groundwater storage.

Although not generally reaching the same magnitude as the two winter flood events described, peaks at some locations did exceed some maxima in 1999 and 2009.

The SMD data shown in Figures B.2 (a-d) reveal that the ground was saturated throughout most of August and September. Even where small deficits existed in early August, these were quickly removed by rain in the first 5 days of that month.

Over a 7-week period, frequent and sometimes heavy rain occurred (see Figures B.3 [a-h]), and total depths were of similar magnitudes as the two sample winter events. Although the Met Éireann "Alert" threshold of 30mm in 24 hours was not exceeded on many days, it must be noted these figures may be misleading as these relate to rainfall days. Often a single large event may be split between two recording days. Table 1-G includes data for 2-day rainfalls on 15 and 16 August, which may be more representative of a 24-hour event, which suggests that at a number of locations the "Warning" or even "Severe Warning" thresholds were exceeded. Although the running cumulative 5-day total rainfalls were at their greatest in mid August, they had reached almost similar levels in early September, when the second flood peak occurred. The dates in the last column of Table 1-G below refer to the last day of each 5-day rainfall event.

Table 1-G Summary rainfall statistics, August-September 2008

Station No	Total rainfall (mm) 31/07 – 15/09	Days with rainfall >30mm	Total 2-day rainfall (mm) 15/08 – 16/08	Max 5-day rainfall (mm) and end date (day/month)
1729	294.3	1	58.2	79.4 (16/8)
1128	288.0	1	40.7	64.8 (15/8)
2230	215.0	1	48.1	50.6 (16/8)
2628	242.2	0	30.5	46.3 (12/8)
1719	246.3	0	20.9	57.3 (10/8)
3022	316.2	2	63.8	116.1 (15/8)
6119	272.1	1	57.4	75.1 (16.8)
6019	373.0	3	38.5	84.8 (5/9)

The weather maps for the period showed low pressure predominated in the vicinity of or over Ireland from the beginning of August, bringing a succession of fronts on a westerly or north-westerly airflow. The localised and intense system which brought rain on 15-16 August is illustrated in Figure 1.6, with a small, deep depression close to south-west Ireland, with associated fronts spread across the country. The second event, in early September was also caused by an intense and localised depression, which moved eastwards along the southern coast from the south-west of Ireland. Figure 1.7 shows the position of the depression and fronts at 18hrs on 4 September, with an occluded, slow-moving front which persisted for 12 hours or more.

Figure 1.6 Synoptic chart, 00hrs 16 August 2008

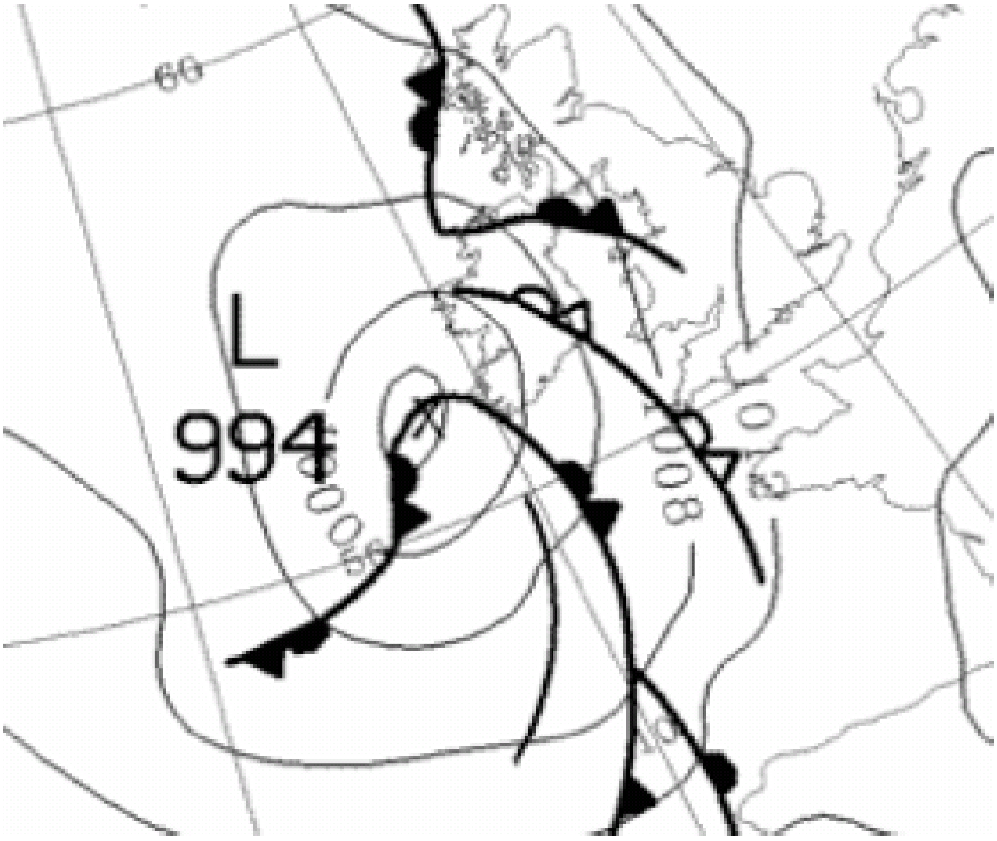
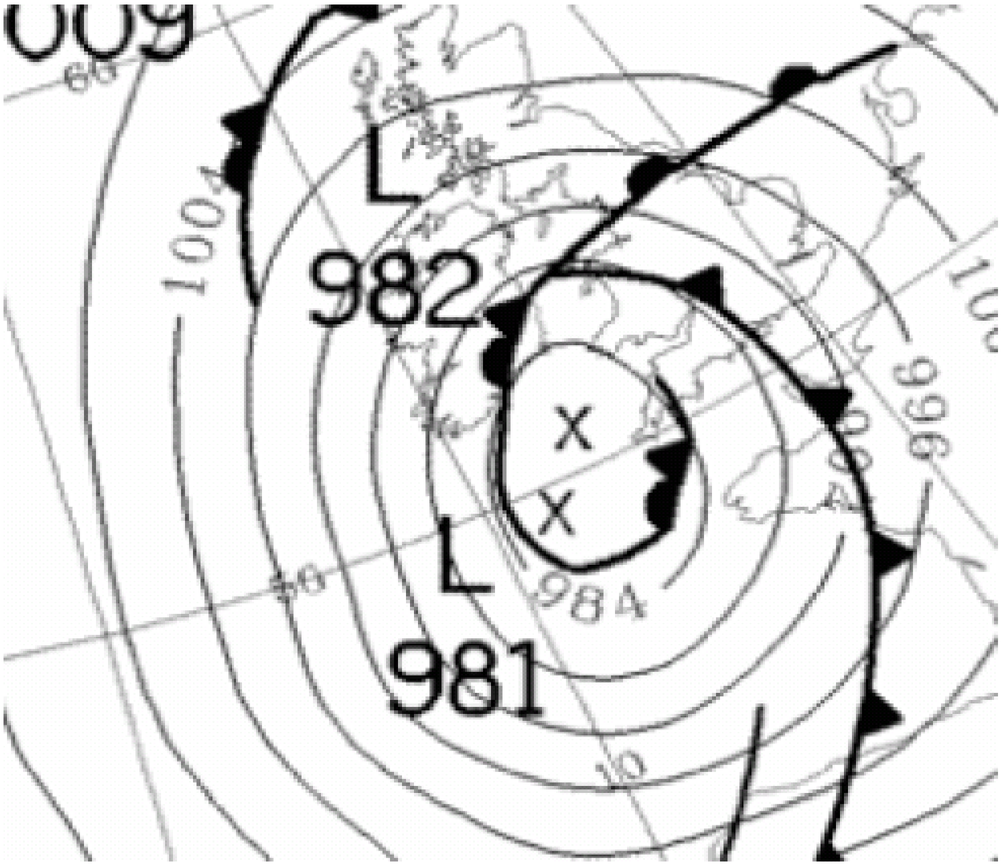


Figure 1.7 Synoptic chart 18hrs 4 September 2008



1.4.4 November 1999 – January 2000

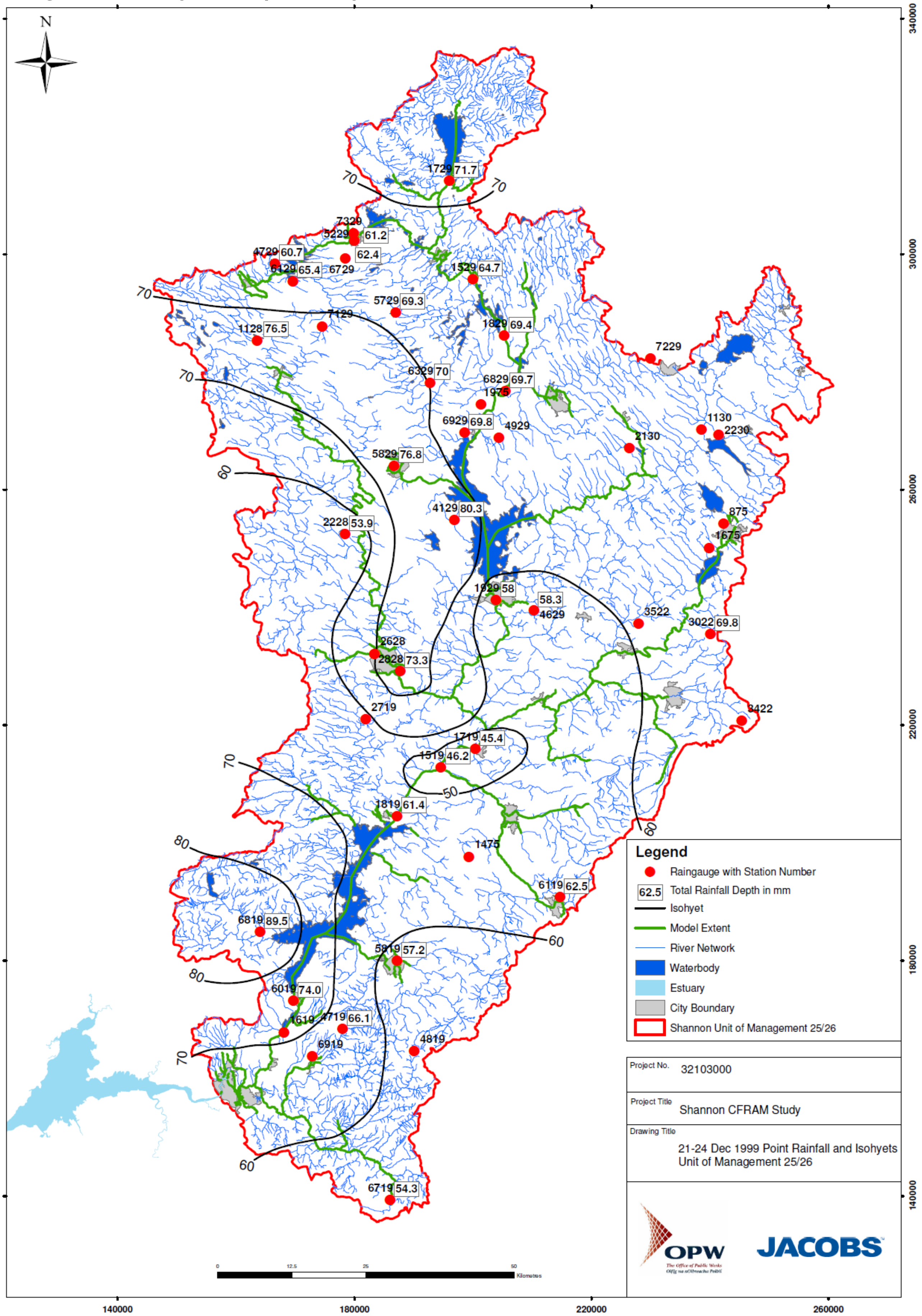
This event produced flood peaks over the 24 to 26 December throughout the whole of the Shannon catchment. Representative hydrographs are shown in Appendix C, Figures C.1 (a–d). An initial flood event occurred over most of the catchment in early November, though there was little response in the limestone catchments of the Boyle and upper Suck. On the more responsive catchments feeding into the middle and lower Shannon, several sharp flood peaks resulted, becoming progressively larger with time (see hydrographs for Mulkear and Ferbane). A build-up of river levels also occurred in the limestone dominated catchments (Beallagill and Tinnacara), although separate flood peaks were less distinct.

The causative rainfall was widespread over the whole area, and as SMD was already at zero or at field capacity (see Appendix C, Figures C.2 (a–d), a high proportion of runoff occurred. A number of periods of 2-3 days of rainfall occurred from late November to mid December, as shown by the hyetographs in Figures C.3 (a–h). Soils were thus maintained at saturation, and cumulative rainfall quantities became significant. Heavy rainfall over the 4 days of 21-24 December resulted in widespread flooding, and similarly heavy falls were widespread over 4-5 November. Some key rainfall statistics are given in Table1-H. The maximum 1-day falls would have exceeded the Met Éireann "Alert" threshold, but as in the other events, it was the accumulation of rainfall over several days that were the cause of the major flood peak.

Table 1-H Summary rainfall statistics, November-December 1999

Station No	Total rainfall (mm) 1/11 – 24/12	Days with rainfall >30mm	Total 4-day rainfall (mm) 21/12 – 24/12	Max 1-day rainfall (mm) and date (day/month)
1729	377.0	4	71.3	41.2 (27/11)
1128	356.3	3	76.5	65.4 (27/11)
2628	298.5	2	73.3	33.8 (4/11)
1719	219.3	1	45.4	32.2 (4/11)
3022	224.2	1	69.8	35.9 (4/11)
6119	250.2	0	62.5	27.0 (24/12)
6019	404.5	2	74.0	42.4 (4/11)

Figure 1.8 Isohyetal map of 4-day rainfall, 21 – 24 December 1999



The 4-day rainfall accumulation for the main flood causing event from 21 – 24 December is illustrated in the isohyet plot in Figure 1.8. Depths are considerably less than the maximum 5-day accumulation of the 2009 event, but the widespread nature of rainfall above 60mm is comparable.

The heavy rainfall in early November that produced the first flood response resulted from a complex alignment of fronts to the east of a trough lying just to the west of Ireland, as shown in Figure 1.9. From the beginning of December, the weather was marked by a succession of fronts and depressions in a north-westerly airstream, which would typically produce unsettled weather with frequent showers. By contrast, the rainy period from 20-24 December was dominated by a south to south-west wind, which is characteristically warm and moist. Rainfall was generated along a trailing front with active secondary depression, as shown in Figure 1.10 controlled by a low over Iceland.

Figure 1.9 Synoptic chart, 00hrs 5 Nov 1999

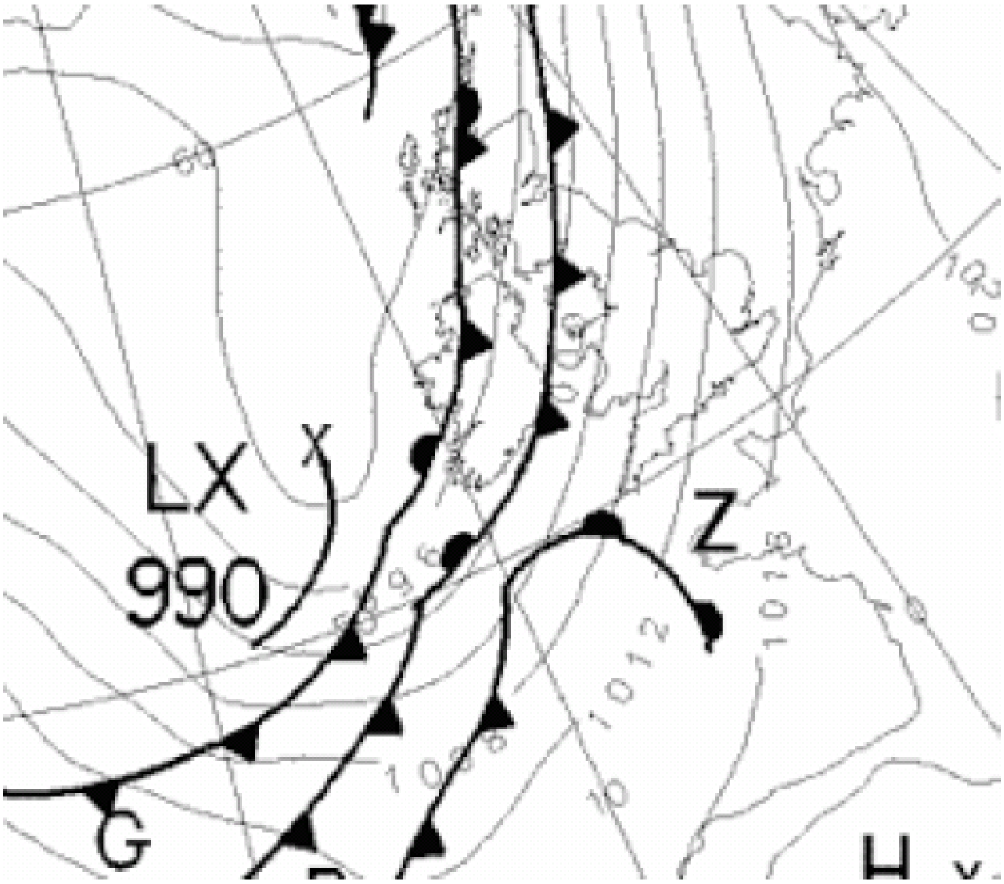
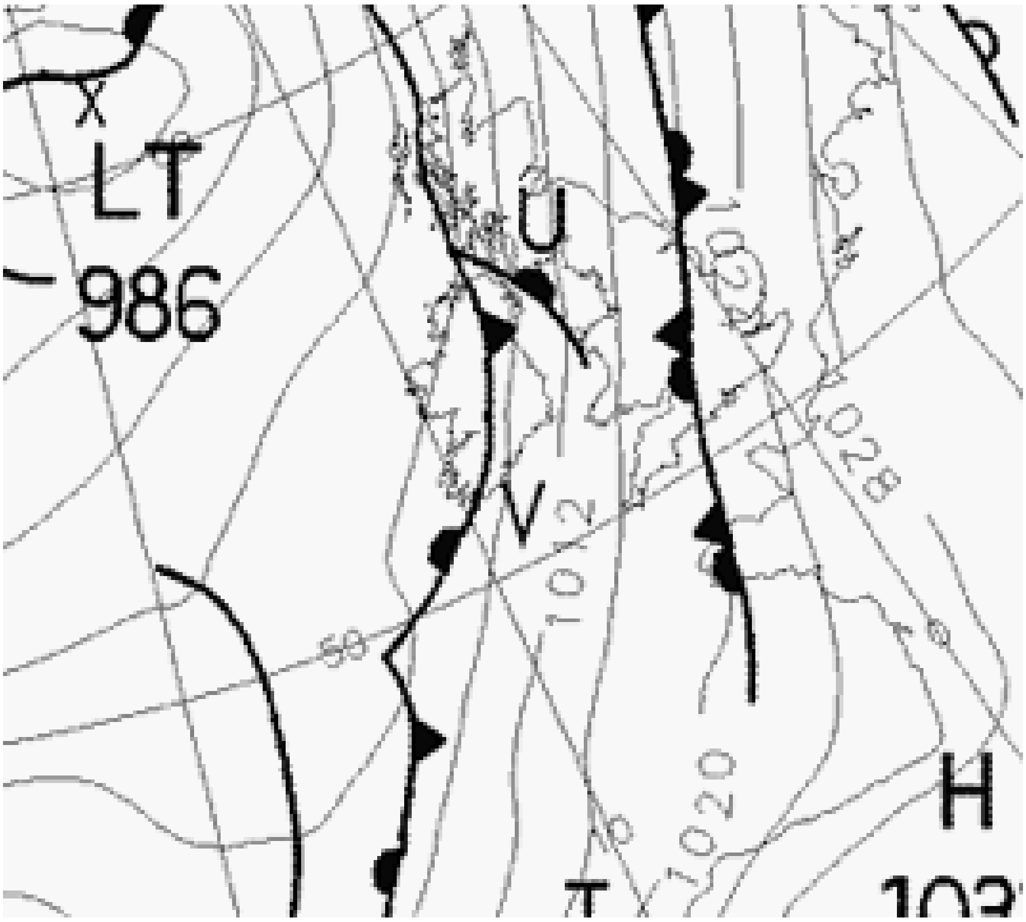


Figure 1.10 Synoptic chart, 00hrs 22 Dec 1999



1.4.5 Localised flooding events

Compilation of flood event reports for all APSRs was made from the OPW "Floodmaps" database. These show that most APSRs are affected by major events, such as the 3 events examined in detail (1999, 2008 and 2009) and other major events that receive a frequent mention were 2005, 1990, 1965 and in particular 1954. A relatively small number of events were identified from the Floodmaps data that occurred outside the major flooding periods at individual APSR sites only. These are largely summer events, and suggest that some locations are more prone to localised events. The events identified are listed in Table 1-I

Table 1-I. Locations and dates of isolated flooding reports from APSRs

APSR Location	River Gauge	Date
CAR 15 Cappamore	25004 New Bridge	10-15 August 1946
CAR 18 Castleconnell	Parteen Weir (ESB)	10-15 August 1946
CAR 45 Newport	25054 Rockvale	10-15 August 1946
		2-7 August 1986
		31 July-6 August 1997
	25308 Waterpark Bridge	10-15 August 1946
		2-7 August 1986
		31 July-6 August 1997
CAR 16 Carrick on Shannon	26324 Carrick on Shannon	2-7 August 1986
		22-27 August 1986
CAR 37 Limerick City	25012 Groody's Bridge	1-5 May 1994
CAR 13 Boyle	26012 Tinacarra	27-31 July 1996
	26108 Boyle Abbey Bridge	27-31 July 1996

On this assumption of local causes, rainfall data from raingauges closest to the relevant APSRs were examined. Significant 1-day rainfalls have been confirmed for each of the events, and are listed in Table 1-J. Many of the daily rainfall totals recorded are as large, or in some cases larger, than those associated with the major flood events examined, and comparison with immediate neighbouring stations indicate that some falls are very localised, e.g. as in example e) Table 1-J.

Table 1-J. Daily rainfall totals (mm) for localised flood events

a) **10-13 August 1946** CARs 15, 18 and 45: Capamore, Castleconnell and Newport

Raingauge No. and name	Date			
	10 Aug	11 Aug	12 Aug	13 Aug
1619 Birdhill	0.3	61.5	13.0	14.5

b) **4-6 August 1986** CARs 16 and 45: Carrick on Shannon and Newport

Raingauge No. and name	Date		
	4 Aug	5 Aug	6 Aug
1529 Drumsna	2.5	33.8	14.1
1729 Drumshanbo	3.5	45.0	3.4
1829 Dromod	2.9	38.1	12.0
1619 Birdhill*	19.3	46.6	6.0
4819 Silvermines Mts*	2.7	59.8	9.9

* CAR 45 only

c) **24-26 August 1986** CAR 16 Carrick on Shannon

Raingauge No. and name	Date		
	24 Aug	25 Aug	26 Aug
1529 Drumsna	3.7	24.0	0.2
1729 Drumshanbo	21.	26.3	0
1829 Dromod	4.0	26.7	0.3

d) **2-4 May 1994** CAR 6 Limerick City

Raingauge No. and name	Date		
	2 May	3 May	4 May
1619 Birdhill	20.0	7.8	5.1

e) **27-30 July 1996** CAR 13 Boyle

Raingauge No. and name	Date			
	27 July	**28 July**	**29 July**	**30 July**
4729 Coolarin	12.5	6.8	2.3	3.0
5229 Boyle	9.6	83.6	3.1	1.2
6129 Frenchpark	9.6	7.5	3.6	3.8
6729 Ballymore	10.5	36.8	4.9	1.4

f) **2-5 August 1997** CAR 45 Newport

Raingauge No. and name	Date			
	2 Aug	**3 Aug**	**4 Aug**	**5 Aug**
1619 Birdhill	5.4	-	91.2*	5.5
4719 Newport	8.0	77.3	33.0	12.4
4819 Silvermines	18.4	68.5	37.5	14.8

* The rainfall recording of 91.2mm for Birdhill is the total rainfall for 3 + 4 August.

The rainfall events in Table 1-J above would appear to be large enough to have caused local flash flooding, but the flash floods may also be the result of local river spates. Except for one example, for CAR 13, Boyle, in July 1996, it has not been possible to examine local conditions in detail.

River gauges 26012 (Tinacarra) and 26108 (Boyle Abbey), both near Boyle (CAR 13), show a response to the local rainfall on 27 and 28 July. The response at Boyle Abbey is particularly rapid, a rise of over 4m occurring in a little over 2 hours. As no sub-daily rainfall data was available, it is not possible to determine the time lapse between rainfall and river response. This confirms that real-time monitoring of rainfall at stations associated with APSRs would be an essential feature of a comprehensive flood forecasting and warning service.

1.5 Probability review, variability and future projections

In order to place the events covered in Section 1.4 in context, this section will examine:

- *the probability characteristics revealed by the Amax analyses of both river flow and rainfall,*
- *an analysis of representative long-term rainfall records, to assess evidence of trends and variability[5], and*
- *latest perceptions on climate change[6].*

The results from these analyses can also give guidance on choice of appropriate thresholds for forecasting and warning.

1.5.1 Results of Amax analyses at hydrological stations

Examination and analyses of the annual maximum discharge was made for a range of stations across Unit of Management 25/26. Many of these had records going back to the 1950s, and so included the historic major floods of 1954 and the 1960s, and included the major event of November 2009. Table 1-K presents the dates of the 3 maximum events at these stations: this shows that the location of major floods can be very variable. The three major floods were notable for their extent and

[5] Guidelines on Analysis of extremes in a changing climate in support of decisions for adaptation. Climate Data and Monitoring WCDMP-No. 72. WMO, Geneva 2009.
[6] Recent Irish weather extremes and climate change. 9th Scientific Statement, Royal Irish Academy Climate Change Sciences Committee, R McGrath et al, 2010.

highest ever flows at some points, but several higher flows have occurred at a number of stations.

Table 1-K. Dates of occurrence of highest 3 floods at hydrometric stations with long records

Station No.	Rank 1	Rank 2	Rank 3
25001	9/12/65	25/12/68	6/2/90
25002	14/9/60	25/9/57	22/1/75
25003	24/12/68	9/12/65	12/12/64
25005	28/11/73	4/12/60	9/12/65
25006	9/12/54	26/12/68	9/2/90
25011	24/12/68	3/12/60	26/8/86
25014	24/12/68	3/12/60	26/8/86
25016	8/2/90	29/1/95	25/12/68
25017	27/11/09	10/12/54	6/12/06
25022	6/10/66	24/12/68	24/9/58
25023	2/8/90	16/12/86	28/1/95
26001	7/10/64	1/11/68	18/10/54
26002	2/10/54	3/11/68	21/11/09
26005	21/11/09	4/11/68	21/10/54
26006	20/10/54	2/11/68	20/11/09
26007	21/11/09	5/11/68	20/10/54
26019	20/11/09	23/10/87	10/12/54

Dates highlighted occur 4 times or more in positions 1, 2 or 3:
12/1965; 11-12/1968; 11/2009; 10-12/1954

The November 2009 flood is clearly one of the major floods on the Shannon. Flood peaks in 1968 and 1954 appear to have taken place at slightly different times: November and December 1968 and October and December 1954. This confirms that a long period of wet weather starting from late autumn is important with regard to flood warning operations, but the variety of dates of flooding also point to the need for careful selection of triggers levels in catchment units.

The annual maximum instantaneous flood peak was used to produce an extreme probability analysis at most of the stations listed in Table 1-K. Overall, the results of the analysis were of good quality and a good degree of consistency exists across the selection of stations. Some plots showed some loss of fit at the more extreme events, which may be associated with problems with the accuracy of ratings at the particular location. As concerns for flood warning are to identify suitable triggers for relatively frequent floods, these discrepancies at higher extremes are not significant for the purposes of this section. From geomorphological considerations and site information, it is generally recognised that out-of-bank flow takes place at return periods of between 2 and 5 years, with the mean annual flood having an average Annual Exceedance Probability (AEP) of 43% (return period of 1 in 2.33 years[7]). The results for a selection of stations is presented in Table 1-L. The table gives the highest recorded maxima, peak flows in the three major events reported in Section 1.4, and the probability estimates for the 10% AEP (10-year flood) and 4% AEP (25-year flood).

[7] Fluvial Processes in Geomorphology, Leopold L, Woolman M and Miller J. 1964

Table 1-L. Recorded peak floods (m^3/s) and probability estimates at selected hydrometric stations

Station No and name	Max recorded flood peak	1999 event peak	2008 event peak	2009 event peak	10% AEP peak estimate	4% AEP peak estimate
25001 Annacotty	158.1	113.4	114.7	123.5	146	159
25006 Ferbane	147.2	91.1	94.9	109.4	115	131
25016 Rahan	36.1	27.1	31.8	28.9	30	34
25017 Banagher	736.4	565.7	450.6	736.4	546	617
25021 Croghan	35.8	32.5	33.7	34.2	33	36
26006 Willsbrook	70.1	-	33.4	64.9	46	54
26007 Bellaghill Brg	224.3	123.1	74.4	221.5	126	145
26008 Johnson's Brg	41.0	29.3	15.6	40.1	31	35
26012 Tinnacarra	109.8	60.6	39.0	108.8	62	73
26019 Mullagh	51.0	31.7	14.8	48.3	32	37
26021 Ballymahon	161.9	-	51.9	119.2*	130	143

* Gaps in data over full flood period

Note: Slight discrepancies exist between values for event peak floods and maximum recorded peak, e.g. for 2009 in some locations. The former are clock 15-minute values as used in Section 1.4.1, and the latter are instantaneous values from a manually checked OPW annual maximum series.

There is a wide range in comparative results between the recorded peak and probability estimates. Some of the 2009 event maxima are much greater than the 4% AEP estimate, whereas at other locations the recorded maxima are below the 10% AEP flood estimate. Rainfall distribution during an event may exert a significant influence on flood behaviour, either through quantity, timing or movement of more active rainfall areas. In the 2009 event, for example, the evident west to east trend in comparative probability level could be the result of the marked west to east variation in total 5-day rainfall. The line of the 100mm isohyet runs in a line from Limerick to Edgeworthstown, all areas to the west receiving more than 100mm, and those to the east less than 100mm. An important point to note is that there is little difference in magnitude between the 10% AEP flood and the 4% AEP flood. Given the non-linear relationship between river level and flow, the differences in river level will be very small. This would suggest that if flood forecasting and warning triggers are set below the 10% AEP-year level, they would provide adequate warning for all major floods. Lower trigger values for more frequently occurring floods, such as those affecting agricultural land, also need to be considered.

1.5.2 Probability analysis of rainfall conditions

The rainfall data made available from Met Éireann included 12 station records extending back to 1941, which is the start date of the current electronic database. Most records contain gaps, and only two raingauges had sufficient continuity for the probability analysis of annual daily maximum rainfall and annual maximum series of

5-day cumulative rainfall. The two stations, 1529, Drumsna and 1929, Athlone are representative of the north and central parts of Unit of Management 25/26.

Large 1-day rainfall depths are usually associated with localised storms, which are most likely to occur in the summer or early autumn months. At the two stations investigated, only two (21/10/02 and 8/12/83) of the two sets of the 5 largest events were winter storms, see Table 1-M. The quantities of rainfall for the maximum events at both stations are very similar, although the stations are distant from one another and the rainfalls were observed during different events. The range of maximum 1-day rainfall values noted in connection with reports of localised flooding (Section 1.4.5, Table 1-J), between 59.8mm and 83.6mm (excluding two events for which no significant rainfall was recorded), is similar in magnitude to that of the top-5 of the long-period records in Table 1-M.

Table 1-M Five highest 1-day rainfalls (mm) at stations with long duration records

Rank	1529 Drumsna		1929 Athlone	
	Rainfall	Date	Rainfall	Date
1	64.8	18/6/55	65.0	22/8/84
2	63.8	5/7/76	59.1	19/9/68
3	56.0	5/8/96	51.2	21/10/02
4	47.9	25/8/70	50.5	13/7/67
5	47.0	6/9/10	48.2	8/12/83

Probability analysis of the 1-day annual maximum series has produced the results shown in Table 1-N. The estimates at both stations are very similar. The depths of the more extreme rainfalls are those most likely to cause flooding in localised areas. It is therefore considered likely that a 1-day rainfall in excess of 50mm could occur at a location somewhere within a large area like UoM 25/26 in any one year. The ability to provide a rainfall forecast of the possibility of 50mm in 24 hours is therefore of considerable use for flood warning. A rainfall depth of 50mm in 24 hours is the current criteria used by Met Éireann for a rainfall Weather Warning.

Table 1-N Estimates of 1-day rainfall (mm) for different annual exceedance probabilities

Station	Annual Exceedance Probability (%)				
	20	10	4	2	1
1529 Drumsna	40.0	45.0	51.3	56.0	60.7
1929 Athlone	40.8	46.3	53.3	58.5	63.6

Heavy rainfall in short durations are also a concern for localised flooding from small, flashy catchments, which may be associated with headwaters of streams in some APSR locations. Met Éireann has provided an analysis of rainfall for a range of sub-daily rainfall periods at four synoptic observations stations, Birr, Claremorris, Mullingar and Shannon Airport, which are geographically well distributed to be representative of UoM 25/26. The maximum rainfall totals recorded for the range of rainfall periods over the *full length* of the station records are given in Table 1-O. These rainfall depths are compared with point estimates for estimated design (trigger) rainfall depths at specific locations from the grid-based national Depth-Duration-Frequency analysis in the hydrological analysis[8] of rainfall presented in the Inception Report for UoM 25/26.

[8] Technical Note 61: Estimation of Point Rainfall Frequencies, D L Fitzgerald. Met Éireann, October 2007.

Table 1-O Maximum rainfalls (mm) for given sub-daily rainfall periods

Station and period of record	30 min	1 hour	3 hour	6 hour	12 hour	24 hour
Birr 1956-2008	25.8	30.2	39.4	39.5	52.7	61.0
Claremorris 1958-1997	23.0	34.6	55.3	72.6	87.5	90.3
Mullingar 1958-2002	26.6	34.5	48.5	62.5	69.8	80.0
Shannon Airport 1958-2003	21.8	28.0	34.0	48.7	48.7	52.8

The review of the three major historic flood events demonstrated the importance of extended wet periods in the development of damaging and widely disruptive events. It has already been noted that rainfall totals on individual days were not large, but the effects of cumulative rainfall and antecedent rainfall over the period immediately in advance of major flood peaks would be an important indicator for warning action. The annual maximum series of 5-day cumulative rainfall has been carried out for the two long-term rainfall records and the results are given in Table 1-P. The 5-day cumulative rainfall quantities identified at the date of occurrence of the peak flows are given in Table 1-Q. These clearly fall into the same broad category as the range of probability estimates. This information is of value when selecting a range of triggers for different flood severity, but it is suggested that trigger values for less severe floods or for use as an early stage of alert could be taken from the annual average 5-day cumulative rainfall, which for both the long-term stations is approximately 60mm.

Table 1-P Estimates of 5-day cumulative rainfall (mm) for different annual exceedance probabilities

Station	Annual Exceedance Probability (%)				
	20	10	4	2	1
1529 Drumsna	75.8	84.7	96.0	104.3	112.6
1929 Athlone	70.6	78.2	87.9	95.1	102.2

Table 1-Q Range of 5-day cumulative rainfall total (mm) associated with time of flood peak

Flood Event	Range of 5-day cumulative rainfall
2009	53.9 - 125.3
2008	46.3 - 116.1
1999	50.9 - 85.8

1.5.3 Historic rainfall variability and future climate projections

Numerous national and international initiatives (e.g. UK Climate Projections [UKCIP] and the UN Intergovernmental Panel on Climate Change [IPCC]) over the last 20 years have brought the topic of climate change much into awareness. Flood forecasting and warning are no exceptions, but although there is a general perception of what climate change might entail, the details of potential specific impacts are poorly understood. The majority of the detail of climate change projection concentrates on temperature, and it is widely acknowledged that projections and observed trends in precipitation are less clear. Those trends and projections that have been postulated have essentially been done on climate considerations, i.e. seasonal, such as increased winter rain. Little has emerged on event changes, and the assumption that future heavy rainfalls will be more extreme

is based on the basic premise that a warmer atmosphere will contain more moisture and be more dynamically active.

A report from Met Éireann in 2001 examined a number of rainfall records in Ireland for long-term trends, over the period from 1941 to 2000. This concentrated mostly on monthly and seasonal rainfall, which showed variable changes of generally small magnitude, but no strong, consistent signal emerged. The long-term trend of annual rainfall, as expected shows considerable range and variation from year to year, with some slight overall upward trend in the west, but little trend in the east. The only detailed analysis for short duration rainfall, from Valentia, showed negligible trend.

A more recent report on climate projections for Ireland, published in 2008[9] also does not present detailed statistics on rainfall, but does consider the problem of downscaling of the broad model projections to the local event scale using airflow direction (850 hPa vertical velocity) as a predictor. Methods of statistical downscaling (SD) and dynamic downscaling (DD) were used. The overall results are inconclusive, and the investigation is summarised in the Met Éireann-UCD Report (Ref.9) as follows.

"*Compared to the reference period 1961-2000, the annual mean intensity changes are small for all stations although in summer and autumn mean intensity increases can be seen for the wetter stations. Decreases in rain day frequency in summer for the drier stations and increases in autumn and winter for the wetter stations are predicted. In the annual average, changes offset each other…. An investigation of changes in large-scale vorticity….. shows that two of the commonly used climate modelling scenarios have a significant trend towards larger values, particularly pronounced in summer months. This is almost certainly the driver of the increased summer rainfall intensity in these scenarios. This index is highly correlated with rainfall (Conway and Jones, 1998) and is a dynamical quantity and therefore well-represented by GCMs (General Circulation Models). While increases in the absolute value of the vorticity field is plausible in climate change scenarios, the question remains whether these changes are realistic or whether the statistical model is too sensitive to such changes.*"

It would therefore be unjustified to make any assumptions with regard to increased incidence and/or magnitude of flooding in the future. As the past may offer some key to the future, it has been considered useful to look more specifically at long-term variations and trends in daily rainfall, primarily to ascertain if:

- *Rainfall characteristics in general is changing;*
- *Incidence of rainy days is increasing;*
- *Incidence of heavy rainfall events is increasing.*

Data from the two rainfall stations, Drumsna and Athlone, used in the probability analyses have also been analysed for trends in annual rainfall totals and the annual occurrence of wet days at the 10% and 1% frequency level. The analysis follows methods used on a study of trends in heavy rainfall events in northern England[10]. The trend of annual rainfall is illustrated by plots of the standardised values, i.e. the annual rainfall as a proportion of the mean annual long term rainfall, in Figures 1.11 and 1.12.

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[9] Ireland in a Warmer World. Met Éireann, University College Dublin, June 2008

[10] Placing heavy rainfall events in context using long time series. Hopkins J, Warburton J, and Burt T. Weather Vol. 65, no. 4, April 2010.

The plot for Drumsna (Figure 1.11) shows that annual rainfall fluctuates frequently on either side of the mean, but ranges are generally small in both directions. The greatest positive and negative deviations are about 35%. A slight overall increase in annual average rainfall is indicated by a straight trend line, but this is small compared with inter-annual variation. When the trend is expressed as a 5-year running mean, some distinct periods emerge. Since 1980, the annual rainfall has consistently been a few percent above average. Between 1960 and 1980 annual rainfall was persistently below average, which contrasted with the period prior to 1960 when totals were nearly always above the long-term average.

The plot for Athlone, Figure 1.12, conversely shows a slight falling trend over the period of record overlaying almost regular annual pattern of positive and negative variations. The 5-year running mean picks out similar long periods with values slightly above or slightly below average. Like Drumsna, most of the period between 1960 and 1980 had less than average annual rainfall, and although wetter years followed 1980, since 1990, totals have fluctuated slightly either side of average.

Figure 1.11 Standardised Annual Rainfall, Drumsna, 1942-2007

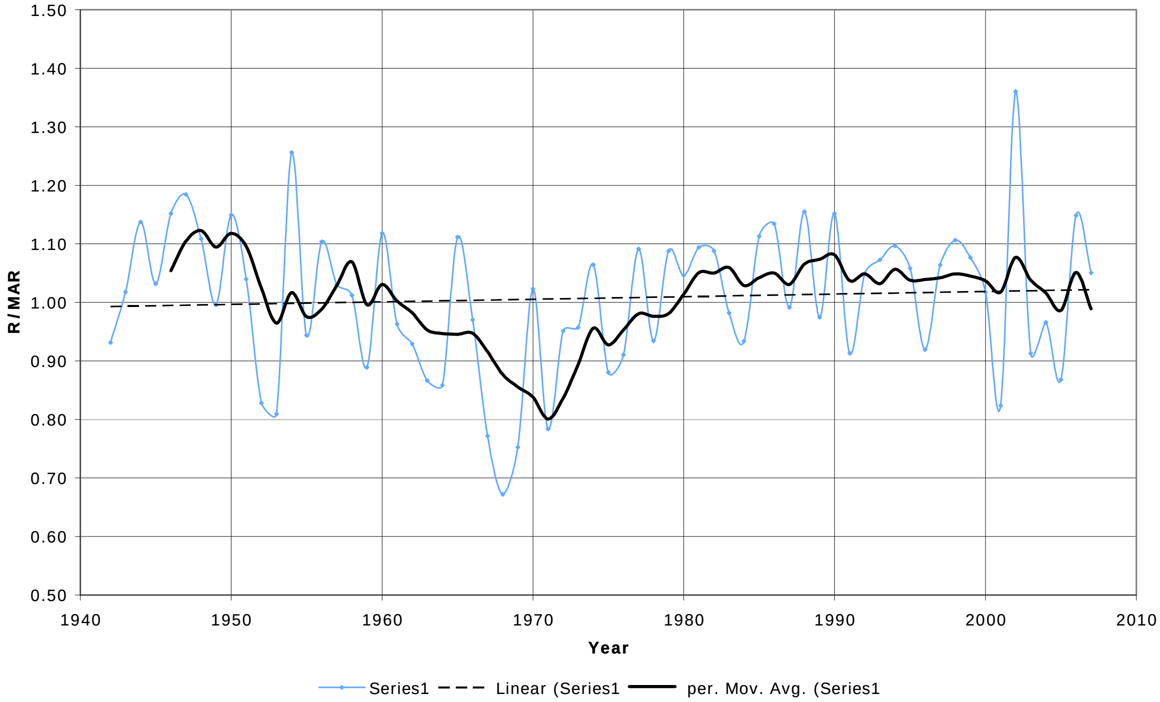
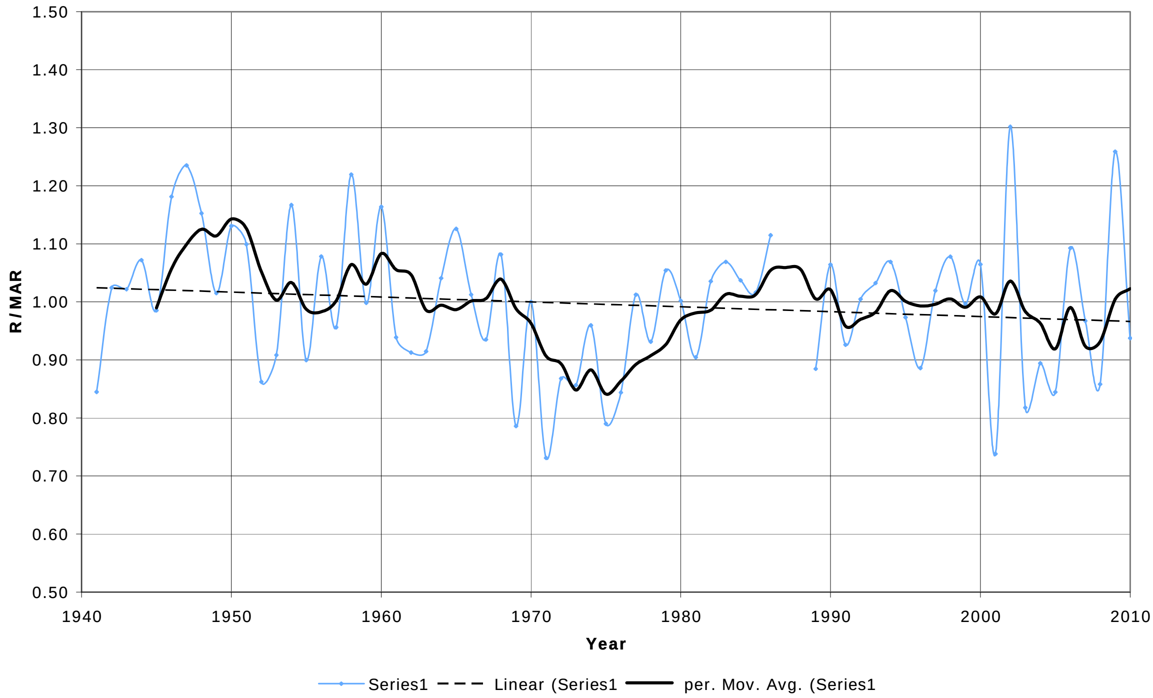


Figure 1.12 Standardised Annual Rainfall, Athlone, 1941-2010



Heavy rainfall is categorised in the method used by Hopkins et al by two indices. T10 is defined as a 1-day rainfall having rainfall greater than the 10% cut-of point for the whole series of days having rainfall above 0.2mm. DR1 is defined by the cut-off point of the top 1% of all days in the record. The index values for the two stations are:

Drumsna	T10 = 10.8mm	DR1 = 21.0mm
Athlone	T10 = 10.4mm	DR1 = 19.9mm

These values are almost identical to the indices applicable to Phoenix Park, Dublin. The total number of occurrences of each category in each year is counted, and the totals at the two stations are plotted in Figures 1.13 and 1.14.

Figure 1.13 Incidence of annual T10 and DR1 events, Drumsna, 1942-2007

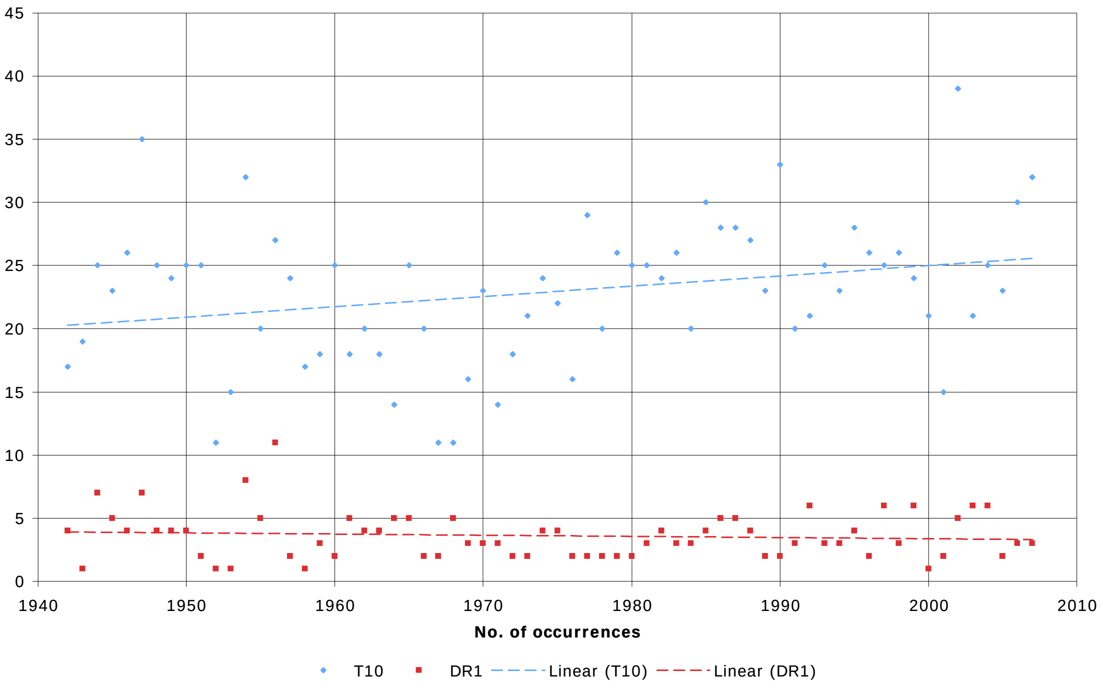
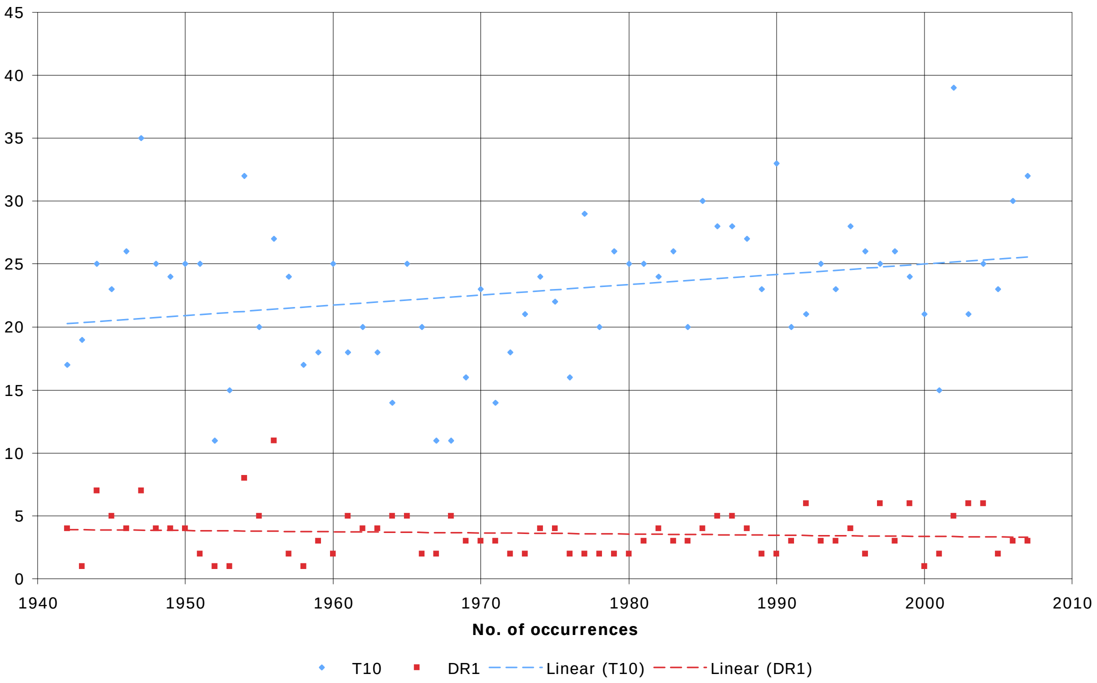


Figure 1.14 Incidence of annual T10 and DR1 events, Athlone, 1941-2010



At Drumsna, the highest number of T10 events in a year was 39 (in 2002): there have been 7 years where T10 has reached 30 or more, 3 of these in the last 10 years. In the larger magnitude DR1 category there have been 9 occurrences where 6 or more events have occurred in a year, but none of these took place between 1956 and 1992.

Similar statistics for Athlone reveal 4 years when the T10 value exceeded 30. The highest number of these events (36) took place in 1947, with 2002 also standing out as a wet year with 32 T10 events. There is not such a clustering of these events

after 2000 as is the case with Drumsna. There were 12 years in the record when the number of DR1 events was 6 or more, but the greatest annual count was again 9. Similarly the record shows a distinct long period of reduced incidence of heavy rain: between 1968 and 1995, a DR1 count of 6 occurred only once.

The overall conclusion to the analyses is that there are few, if any, pointers to persistent, uni-directional change in rainfall patterns over time; and there is certainly no basis for extrapolating trends into the future. The main signal to emerge is that considerable inter-year variability exists, and there are extended periods when overall wetter or drier conditions can predominate. These findings also confirm that careful evaluation of past conditions can be used to confidently define flood forecasting models, and operational warning triggers.

2 Present Flood Warning Provision

There are no formal provisions or flood warning on the River Shannon, although in serious flood conditions there is a good degree of informal liaison between OPW and local authorities, which have the responsibility for emergency response. During periods of high flow, the Electricity Supply Board (ESB) issues predicted water levels from their informal forecasting system. Similarly, Met Éireann has no responsibility *per se* for flood warning, but as part of their public service remit, do provide severe weather warnings, which include heavy rainfall warnings. These however are generalised, and not aimed at a specific user, but are recognised as being beneficial to OPW and local authorities.

Met Éireann include quantitative rainfall forecasts in their local authority/public service rainfall warnings, and the criteria are given in Table 2-A. Met Éireann will issue warnings below these criteria if a prior very wet spell has resulted in saturated ground. This was certainly the case in the three major events reported in Section 1.4, above, where 1-day rainfall totals rarely would have achieved the "Alert" category.

Table 2-A Met Éireann Warnings Criteria for rainfall

Weather Alert	Weather warning	Severe Weather Warning
30mm in 24 hours 25mm in 12 hours 20mm in 6 hours	50mm in 24 hours 40mm in 12 hours 30mm in 6 hours	70mm in 24 hours 50mm in 12 hours 40mm in 6 hours

Met Éireann also provides quantitative rainfall forecasts for 6-hour and 24-hour rainfall accumulations for the Electricity Supply Board (ESB) on the Shannon. The forecasts are a combination of graphical and tabular presentation, divided into clock-hour segments, i.e. 0z-06z, 06z-12z, etc., and cover a period of 6 days. A typical rainfall forecast is illustrated in Figure 2.1. The forecast is broken down into four units of the Shannon catchment, and the quantitative variation shown over the units indicates that the model forecasts are capable of definition into area units suitable for the scale of larger catchment subdivisions within the Shannon.

Figure 2.1. Example of Met Éireann rainfall forecast for ESB

3 Suggestions for Developing a Flood Forecasting System

3.1 General

3.1.1 Background Information

The following guidance, taken from a paper by Bruen[11], although some years old, provides a useful summary of the range of technical requirements for flood forecasting systems. The emphasis on the various components depends on the specific conditions of the catchment(s) in question.

"The technical requirements of a flood *forecasting system are:*

i) *A real-time data collection sub-system for receiving and processing the relevant meteorological information (particularly rainfall from telemetry and/or radar), the discharge data at appropriate gauged sections in rivers (or water levels and rating curves), impoundments, etc. and soil moisture measurements if required. These may involve manual recording gauges, automatic recording gauges, terrestrial data collection platforms, ground-based radars, satellites, airborne sensors, etc. and extensive use of GIS to present such information in useful format.*

ii) *Access to the outputs of a numerical meteorological forecasting sub-system i.e. Numerical Weather Prediction (NWP) models for forecasting meteorological inputs e.g. the Quantitative Precipitation Forecasts (QPFs) over the required lead-time of the flood forecasting model.*

iii) *A sub-system for optimally combining the data from various sources and for providing a feedback mechanism for recalibration of the measuring tools and techniques and for initialisation of model error correction.*

iv) *A catchment modelling sub-system, embedded in a user-friendly interface, to estimate the total discharge at the catchment outlet, at the required time intervals, along with a corresponding statement of uncertainty.*

v) *A sub-system comprising a hydrodynamic or a hydrological channel routing model to estimate the movement of the flood wave along the channel, the water levels and the effects of dyke breaches, reservoir operation and the interaction with the flood plain and flooded areas, giving a flood inundation forecast.*

vi) *An error correction sub-system having an algorithm for improving the estimates of discharge based on recent feedback from river gauge data.*

vii) *Appropriate communications, GIS networks and decision support systems, producing forecast details at various levels, map forecasts showing flood inundation in real time, etc.*

These requirements need to be balanced according to the specific needs of the at-risk communities, the nature of the floods and flood risk, always allowing for financial and capacity constraints."

The organisational framework through which these technical requirements can be met has progressively evolved and refined over recent years. Whereas once flood warning was somewhat distant from flood forecasting, and generally the responsibility of a catchment management agency, international good practice now

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[11] Bruen, M., 1999, Some general comments on flood forecasting, Proc. EuroConference on 'Global Change and Catastrophe Risk Management': Flood Risks in Europe, IIASA, Laxenburg, Austria. 6th-9th June 1999).

recognises the essential interfacing of meteorological and hydrological services. In many countries flood forecasting and warning services are provided through a dedicated flood forecasting and warning centre, either jointly run between meteorological and hydrological services, or with clearly defined roles and responsibilities of both types of service to a parent organisation. This high level of co-ordination extends to the involvement of operating partnerships with a range of stakeholders, from emergency services to communities. This approach is well defined by recent WMO Guidelines[12], which highlights the following features:

- *The roles and responsibilities of national meteorological and hydrological services (NMHSS);*
- *Effective early warning;*
- *Knowledge of risk;*
- *Monitoring and warning service;*
- *Dissemination and communication;*
- *Warning and response;*
- *Monitoring, review and capacity building.*

3.1.2 Information from the OPW "Strategic Review"

A "strategic review" of the options for flood forecasting and warning has recently been completed by consultants for OPW[13]. The OPW consultants were commissioned to carry out a strategic review of options for flood forecasting and flood warning in Ireland. The consultants' final report has been received and the OPW will shortly be consulting with the primary stakeholders identified in the report. This review has considered a number of options for the structure, scope and operation of flood forecasting and warning systems at local, regional and national levels. The findings of the strategic review will guide how a Shannon flood forecasting and warning system might be operated.

3.1.3 Consideration of Lead Time

The provision of sufficient lead time in which to take necessary preparation and response actions is a key feature of a flood forecasting system. Meteorological forecasts have improved markedly over recent years with the widespread use of numerical forecast techniques. Forecasts of general conditions, e.g. rain-bearing systems are now consistent for lead times of 2-3 days, particularly in Ireland where westerly circulation predominates. At shorter lead times, the confidence on the occurrence of particular conditions improves, and forecasts become more focussed spatially, and on quantitative precipitation forecasts. Forecasts of severe weather with a lead-time out to 36-hour may therefore be treated with sufficient confidence for preliminary decision-making in flood forecasting operations.

The catchments within Unit of Management 25/26 are sufficiently large to provide long enough lead times for more detailed flood forecasts to be made from monitoring of river conditions. The detailed study of the three major events (Section 1.4.1) has allowed some analysis of times to peak at a number of river gauging stations. Where a flood response was clear, and unaffected by follow-on events, the lag time was measured as the time from commencement of river rise to the time of flood peak. These results are summarised in Table 3-A.

[12] Guidelines on Early Warning Systems and Application of Nowcasting and Warning Operations. WMO/TD-No. 1559, PWS-21. WMO, Geneva, 2010.
[13] Strategic Review of Options for Flood Forecasting and Flood Warning in Ireland, JBA Consulting, UK Met Office. Office of Public Works, 2011.

Table 3-A Times to peak in major flood events

Station number and name	Date of Flood Event			
	Nov 1999	Dec 1999	Aug-Sep 2008	Nov 2009
25001 Annacotty	13 hrs	22 hrs	16 hrs	14 hrs
25006 Ferbane	32 hrs	30 hrs	34 hrs	31 hrs
25016 Rahan	16 hrs	21 hrs	19 hrs	22 hrs
25021 Croghan	16 hrs	-	28 hrs	19 hrs
26006 Willsbrook	No data	No data	58 hrs	100 hrs
26007 Bellagill	84 hrs	-	Indistinct	98 hrs
26008 Johnston's Bridge	46 hrs	5 days	68 hrs	>5 days
26012 Tinnacarra	105 hrs	>5 days	Indistinct	>5 days
26019 Mullagh	36 hrs	67 hrs	50 hrs	78 hrs
26021 Ballymahon	No data	No data	28 hrs	Incomplete

Two sets of results were obtained from the 1999 flood event, as the initial flood in early November provided an ideal discrete event from a single rainfall input. The flood peak in late December was more complex, but provided some clear single flood responses. Overall the results show reasonable consistency, but some irregularity may be the result of local backwater effects or out of bank flow. The event analysis has also shown that the Lower Suck and Callows area have lead-times (from commencement of river rise to the time of a major peak) of the order of three or more days.

For the purpose of flood forecasting, the results show that adequate lead-time exists for modelling and response to be successful.

3.1.4 Uncertainty and Accuracy

When dealing with flood forecasting, and subsequent warning and operational management, the consequent decisions may involve dramatic consequences (economical losses, casualties, etc.). These decisions may need to be made under stress, and with some uncertainty on the evolution of future events.

Hydrological and meteorological forecasts have inherent errors and uncertainties. As these forecasts are predominantly made through models, they will be inevitably affected by different sources of errors, which can be summarised as:

- *Model errors;*
- *Model parameter errors;*
- *Boundary condition errors;*
- *Initial condition errors;*
- *Observation errors;*
- *Input forecast errors.*

The uncertainties in flood forecasting varies somewhat from more straightforward engineering design, where measures such as error bands, confidence limits, tolerance, etc, can be quantified. Joint probabilities may be assessed and a risk-impact assessment be achieved. Meteorological and hydrological forecasts both share an important factor of time, as well as magnitude, so uncertainty arises because of:

- *A forecast event does not occur;*

- *An un-forecasted event occurs;*
- *The magnitude of the forecast event is exceeded, or less than the actual event;*
- *The forecast timing is late or early in relation to the actual event.*

In the case of this present study, which is a preliminary review of the potential for flood forecasting, it has had to be assumed that data used has been quality controlled to a good standard, but some level of inherent uncertainty exists in measurement and estimation, e.g. flow-rating curves. These will continue to exist in any flood forecasting system, and the impact of such uncertainties can only be fully explored when outcomes can be focussed on receptors and impacts. We would propose that any flood forecasting system adopted should include verification as an integral part of the operation. Forecast verification is carried out periodically, e.g. at the end of a flood season, and a number of measures may be employed:

- *PoD (Probability of Detection);*
- *Hit Rate (HR);*
- *FAR (False Alarm Rate);*
- *The Brier skill score;*
- *Continuous Measures, e.g. bias (mean error), RMS (root mean square error) and MAE (mean absolute error).*

These indices obtained are all relative values, i.e. there is no "right" or "wrong" score, so outcomes are reviewed by noting if the score "improves" or otherwise. A selection of criteria, together with their rationale, are summarised in a document, publicly available at the Australian Bureau of Meteorology website: http://www.bom.gov.au/bmrc/wefor/staff/eee/verif/verif_web_page.html

The exact numerical comparison of forecasts and observations, for example of flood peaks and rainfall depths, produces results that are largely unhelpful. Recent attempts to establish an "independent" assessment of public service forecasts (the BBC "Weather Test") have stalled whilst the participants agree the methods and variables to be used[14].

Because of the use of ensemble predictions in numerical forecasting, the practice now in rainfall and flood forecasting is to provide forecasts in terms of probability. Thus a particular event is defined as having a given probability of occurring. Although this may be understood by professional forecasters, there may be problems in communicating a statement like "the probability of flooding in the next 12 hours is 67.5 %" to an end-user. Flood forecasters must be able to explain the uncertainty as a form of utility function, which can demonstrate the expected benefits or the expected damages related to the forecast.

3.2 Specific Forecast and Warning needs for the Shannon

3.2.1 General arrangement of requirements

The review of major flood events in Section 1.4.1 has shown that the principal cause of major flooding within Unit of Management 25/26 is prolonged rainfall, particularly with recurrent wet periods. It is clear that a majority of APSRs are primarily at risk from these large-scale events. Each of the three major events analysed exhibited the same conditions:

[14] The BBC 'Weather Test', Weather News. Royal Meteorological Society, Weather, Vol. 66, no 3, March 2011.

- *Soil moisture deficit (SMD) at or close to zero;*
- *Build-up of antecedent rainfall;*
- *Field capacity being exceeded throughout the rainy period;*
- *Persistent passage of rain-bearing systems;*
- *Individual flood peaks or general river levels rising progressively over a period of weeks.*

Thus an early warning system for major flooding, which would combine information on catchment wetness, antecedent rainfall and river conditions, would appear to be of particular value. Each of the contributory factors lend themselves to the adoption of a trigger or baseline reference value being exceeded, with a more focussed system of hydrological flood forecast models being more important as the potential flood status is identified.

Observations that identify the development of the contributory conditions to flooding are for the most part already carried out, or the instrumentation network already exists. However, for a dedicated flood forecasting and warning system, they would need to be co-ordinated and developed, and the following components are proposed.

1. The use of numerical data feeds for soil moisture deficit (SMD) at observing sites within the catchment, i.e. Gurteen, Knock Airport, Mullingar and Shannon Airport, on a daily basis. As SMD data is recorded for three soil categories (well, moderate or poorly drained), the prevalence of relevant conditions in different catchments would need to be assessed.

2. Availability of daily forecasts of weather conditions up to 5 days ahead (T+120hrs), with particular emphasis on timing and quantity of rainfall. Met Éireann routinely use numerical forecasts, which are used to provide a sequence of rainfall forecasts as maps. This information would need to be provided in digital form. It is suggested that quantitative rainfall forecasts could be provided for the following four subdivisions within Unit of Management 25/26:

- *The Shannon catchment upstream of Athlone – Lough Ree, i.e. the Upper Shannon, Inny and Rhin rivers;*
- *The River Suck catchment;*
- *The Brosna and Little Brosna catchments;*
- *The Lower Shannon catchment, comprising Lough Derg downstream to Limerick.*

3. Maintaining a continuous telemetry data feed of water levels at a representative network of existing hydrometric stations. Conversion of level into flow will be a function within the model system if discharge, rather than level, is a critical factor, e.g. for sluice operation or gate settings. The proposed network should have the dual function of indicating the general behaviour of the six main sub-catchments within Unit of Management 25/26, and to provide the necessary inputs into the flood forecasting model. Some network locations may be relevant to APSRs and IRRs, though these may require more specific local warning points, which is discussed further below. To provide effective warning from upstream to downstream, from observations and from forecast models, at least two hydrometric stations are needed in each catchments segment. The suggested Primary Flood Forecasting System network is given in Table 3-B: the locations of the stations are shown in Figure 3.1.

4. Establishment and operation of a network of telemetered recording raingauges. These would serve a twofold purpose of continuously monitoring rainfall to provide information on antecedent conditions, and to provide inputs into flood forecasting models. This data is currently only available retrospectively, and it will be necessary to convert a selection of these gauges to be automated for use in the flood forecasting and warning system. Similar criteria and representativeness for catchment definition and model inputs is required for rainfall observation as for hydrometry, and initial proposals are given in Table 3-B and illustrated in Figure 3.1.

Figure 3.1. Hydrometric Networks for Primary Flood Forecasting System

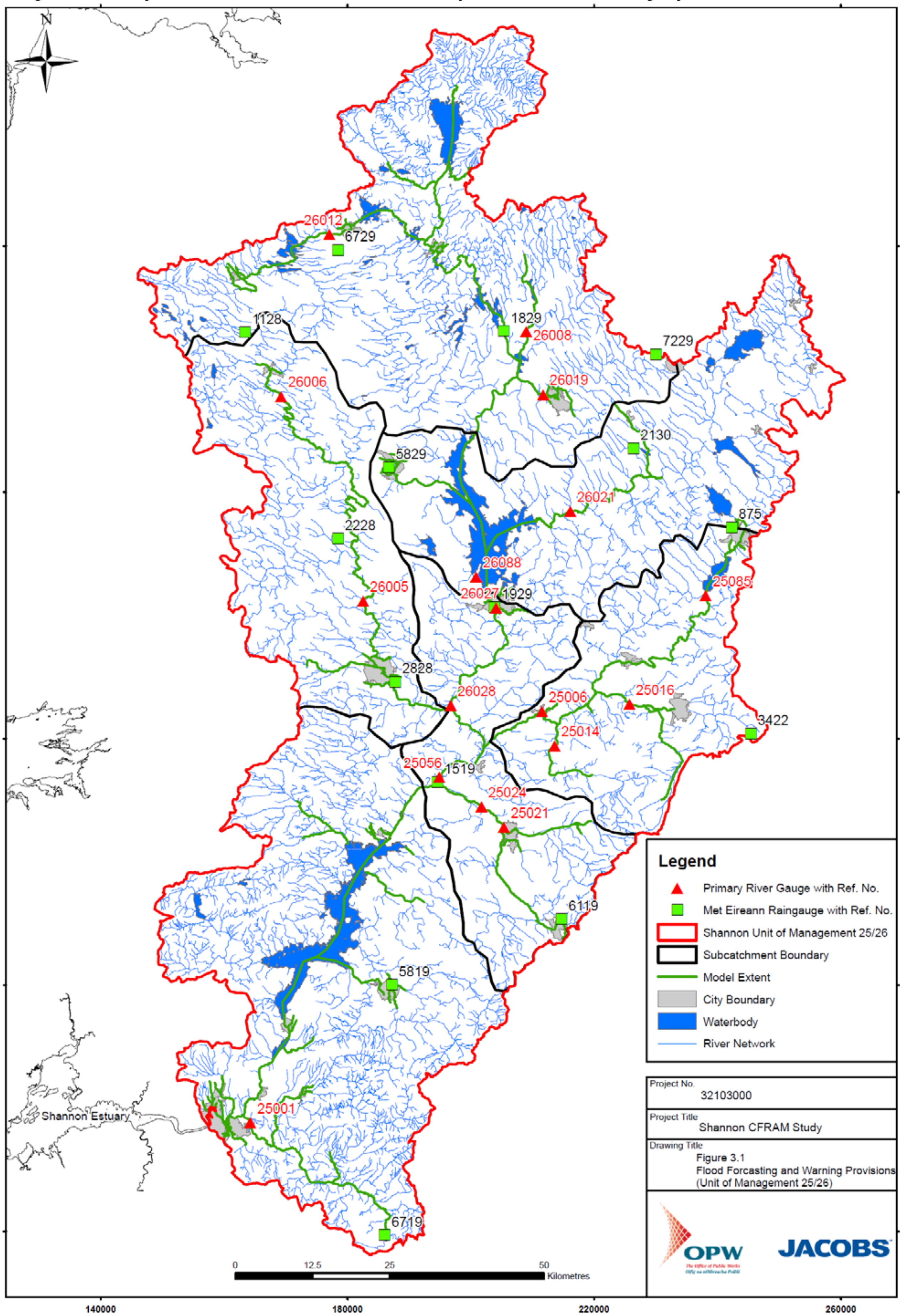


Table 3-B Raingauge and hydrometric network for catchment units, Primary Network

Catchment	Raingauge	River Gauge
River Suck	1128 Loughglinn	26006 Willsbrook
	2228 Ballygar	26005 Derrycahill
	2828 Ballinasloe (Pollboy Lock)	
Upper Shannon	6729 Ballymore	26012 Tinacarra
	1829 Dromod (Ruskey)	26008 Johnston's Bridge
	7229 Granard (Ballymore)	26019 Mullagh
Tributaries to Lough Ree	2130 Rathowen (Killinagh)	26021 Ballymahon
	5829 Roscommon Vocational School II	26088 Hodson's Bay
Central Shannon	1929 Athlone OPW	26027 Athlone
River Brosna	875 Mullingar	25006 Ferbane
	3422 Geashill	25016 Rahan
		25085 Clonsingle
River Little Brosna	1519 Meelick (Victoria Lock)	25021 Croghan
	6119 Roscrea (New Road)	
Lower Shannon	5819 Nenagh (Connolly Park)	25056 Meelick Weir
	6719 Limerick Junction	25001 Annacotty
IRR2 Lumcloon PS		25014 Millbrook
IRR5 Lanesborough PS		New site
Shannon Callows		26028 Shannonbridge
		25024 New Bridge

Table 3-C Raingauge and hydrometric network for APSRs (CARs), Secondary Network

Catchment	Associated CAR	Raingauge	River Gauge
River Suck	CAR 19 Castlerea	1128 Loughglinn	26006 Willsbrook
	CAR 8 Ballinasloe	2828 Ballinasloe (Pollboy Lock)	26007 Bellagill
Upper Shannon	CAR 7 Ballaghaderreen		26014 Banada Bridge
	CAR 13 Boyle	6729 Ballymore 5229 Boyle (Marian Rd)	26012 Tinacarra 26108 Boyle Abbey Bridge
	CAR 16 Carrick on Shannon	1829 Dromod (Ruskey)	26324 Carrick on Shannon
	CAR 26 Drumshanbo	1729 Drumshanbo	26109 Drumshanbo
	CAR 41 Mohill	1529 Drumsna	26042 Mohill
Tributaries to Lough Ree and Central Shannon	CAR 2 Abbeyshrule	2130 Rathowen (Killinagh)	26104 Ballinalack
	CAR 27 Edgeworthstown	2130 Rathowen	26305 Glen Lough Lower
	CAR 51 Roscommon	5829 Roscommon Vocational School	Site to be identified
	CAR 6, Athlone	1929 Athlone OPW	26088 Hodson's Bay
River Brosna	CAR 42, Mullingar	875 Mullingar	
	CAR 54 Shannon Harbour	1719 Banagher	25006 Ferbane
	CAR 47 Pollagh CAR49 Rahan		25016 Rahan
	CAR 30 Kilbeggan CAR 21 Clara	3522 Horseleap	25085 Clonsingle
	CAR 23 Clonaslee	3422 Geashill	Site to be identified
	CAR 31 Kilcormac		Site to be identified
River Little Brosna	CAR 11 Birr		25021 Croghan
	CAR 52 Roscrea	6119 Roscrea (New Road)	
Lower Shannon	CAR 43 Nenagh	5819 Nenagh (Connolly Park)	
	CAR 48 Portumna	1819 Portumna OPW	25056 Meelick Weir
	CAR 37 Limerick City		25001 Annacotty
	CAR 12 Borrisokane	1475 Gurteen	Site to be identified
	CAR 34 Killaloe CAR 46 O'Briensbridge CAR 18 Castleconnell	1619 Birdhill	One site to be identified, d/s end of Lough Derg
	CAR 45 Newport	6919 Newport (Coole)	25308 Waterpark Bridge
	CAR 15 Cappamore	Site to be identified	25004 New Bridge

The following triggers for alerts and early warnings are suggested.

- *Soils are thoroughly wetted, i.e. SMD = 0mm, and/or field capacity, SMD = -10mm achieved in one of the soil classes;*
- *Antecedent rainfall, measured as a 5-day running total, reaches a magnitude at which it has been shown that further rainfall could produce flooding;*
- *Medium-range weather forecasts, indicate a period of wet weather, with NWP estimates exceeding 30mm for a 5-day period;*
- *River levels reaching an "early warning" threshold.*

3.2.2 Provisional components of a flood forecasting and warning system

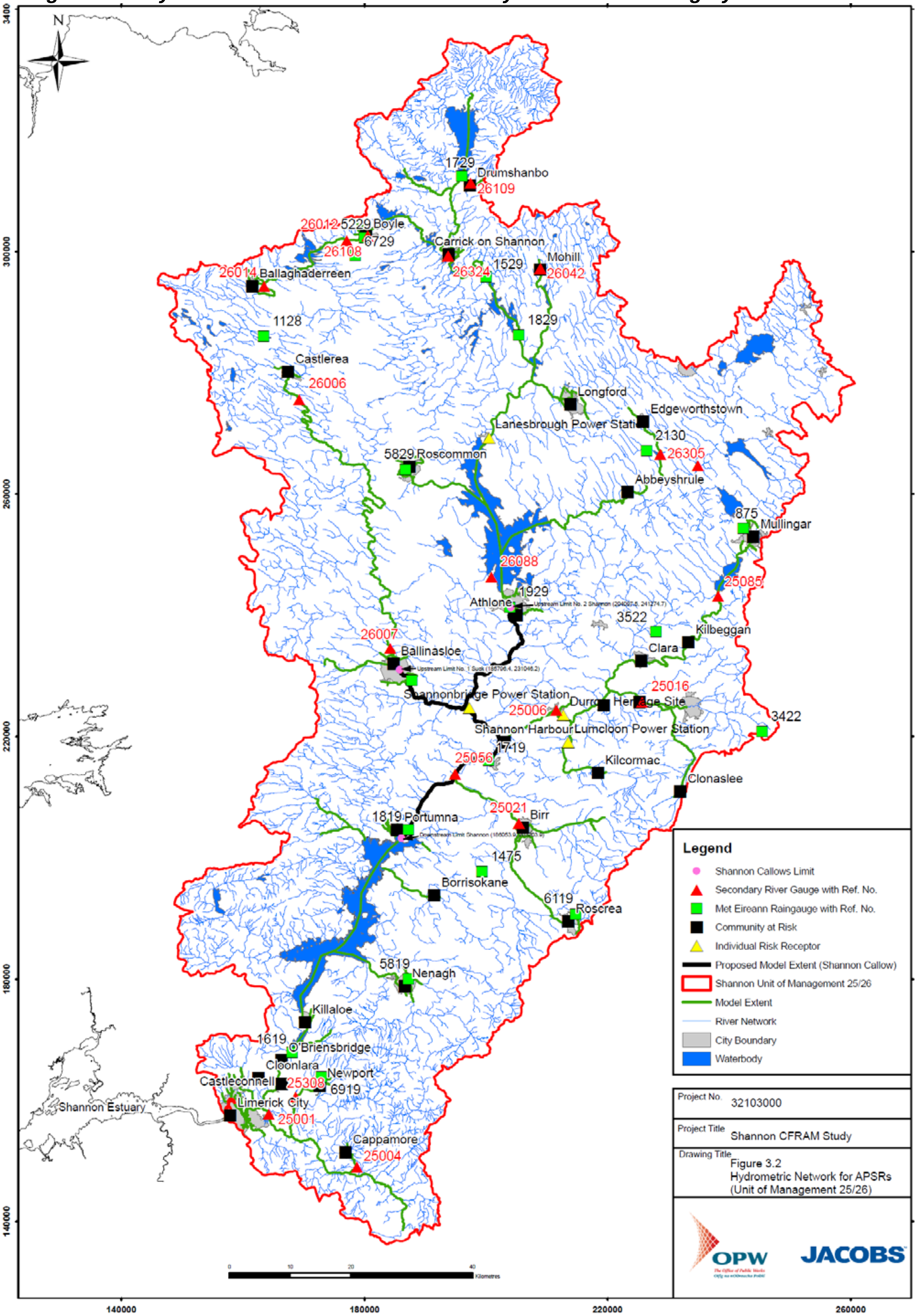
The system described above would operate to provide information on current status for overall monitoring purposes and also to provide routine model updating at daily or at shorter intervals (6 or 12 hours), depending on final detailed design. The achievement of trigger levels, as well as producing a specific alert status message, would also initiate a more frequent "real-time" set of data feeds, to provide inputs at short time-steps for updating hydrological and hydro-dynamic models comprising the flood forecasting and warning system.

The two levels of activity will use the same networks and information delivery and updating system, and so would not be independent functions as at present, where there is only ad-hoc linkage between meteorological and river forecasts to serve emergency and flood management agencies. The real-time observations and models will provide warnings of imminent and serious flood risk by producing a forecast hydrograph for a suitable period, which will be used to generate more specific advice and warnings, and these are considered in Section 3.3. The critical requirement for the issue of forecasts and warnings is the lead-time provided at risk sites which must be sufficient for response actions to be instigated. The more rapid response of some catchments, e.g. that of the river Mulkear at Annacotty (hydrometric station 25001) may require frequent model updates. The extent of forecast period will be defined through discussion between modellers, flood forecasting managers and users. Depending on the model updating interval and the nature of catchments involved, a forecast period extending out to 48 or 72 hours from forecast time is suitable for the nature of the catchments concerned.

APSRs and IRRs are subject to specific site risks, which in the majority of locations can be related to river forecasts from the overall monitoring-forecasting network. In some localities, where flood history suggests sensitivity to local streams or rainfall conditions, more specific warning information than possible from the general network may be required. In these cases APSRs and IRRs will need to be provided with raingauges or river gauges that will respond to site-specific trigger data, and in some cases will need arrangements for production of automatic alarms outside the framework of the flood forecasting and warning mode. The raingauge and hydrometric network required to meet this Secondary Flood Forecasting and warning needs for APSRs in shown in Figure 3.2 and Table 3-C.

Figure 3.2 also shows the locations of Individual Risk Receptors (IRR) and the Shannon Callows. As these are all located on main river sites, then it may be possible that specific forecast/warning information can be produced from individual model applications from the main catchment model structure.

Figure 3.2. Hydrometric Networks for Secondary Flood Forecasting System



3.2.3 Arrangements for meteorological inputs

At present, any meteorological inputs to flood warning are by direct contact between staff at Met Éireann and OPW, on an ad-hoc basis. Integration of meteorological and hydrological information for a real-time flood forecasting and warning system will require that this interaction must become formalised and automated to a high degree. The formalisation of arrangements should be made through appropriate service agreements which will primarily be for the provision of meteorological data from the meteorological service to the organisation that will be responsible for the issue of flood alerts. Agreements have to define the extent of data to be provided, means of delivery, regularity of provision of information and standards of service on timing and quantity. In such arrangements for various flood forecasting operations, the information and data from the meteorological service covers.

- Data and forecasts;
- Radar imagery or digital data;
- Customised warnings;
- Direct contact between duty forecasters.

Although the basis of these services exists within Met Éireann, their formalised provision will require adaptations and development of services and increased staff involvement. The dependence on rapid transfer of digital data and information also requires the development of computer system interfaces and protocols, and experience has shown that providing these facilities are not trivial undertakings.

The dissemination of alerts to the public can make use of existing services like email, web pages and GSM. The delivery of data from the meteorological service (e.g. radar imagery and other digital data) to the flood alert organisation is likely to require dedicated communication systems, as publicly available services such as email, FTP, GSM, etc. may lack the reliability and resilience needed to provide a critical public service. Such a critical service has to deliver data with very high reliability, greater than 99% of all reporting intervals over a prolonged period (e.g. one month), and with outages limited to only short durations, e.g. no longer than three consecutive hours. Therefore an independent joint communications system may need to be set up. As well as setting up suitable telecommunications arrangements, attention needs to be paid to IT security to ensure a reliable and safe system.

Even approximate costing of the provision of these services is not possible without better understanding of the forecast service and model requirement, and would be the subject of negotiation between the relevant parties.

3.2.4 Costs and investment in equipment and services

A summary of instrument requirements defined in Section 3.2.1 above (Figures 3.1 and 3.2 and Tables 3-B and 3-C) is given in Table 3-D. The majority of raingauge and river gauge locations already have instrumensts: the numbers of instruments required include three new raingauge sites and four new river gauge sites. The Project Brief requires outline costs; we have taken these from recent Jacobs' project experience in UK and Ireland, and our current knowledge of similar flood forecasting systems. The operator's staff costs have been omitted from these cost estimates.

Table 3-D Summary of instrumentation requirement

Application	**Telemetry recording tipping bucket raingauges**	**Telemetry water level recorders**
Primary System Catchment Units	15	14
Individual Risk Receptors	0	2
Shannon Callows	0	2
Secondary System Communities at Risk	8	12
Total	**23**	**30**

The equipment for the tipping bucket raingauges and water level recorders will have similar costs, a budget estimate of €2,000-€2,500 per unit. The installation will comprise the measuring instrument, logger, GPRS and cabling, but the operator may have to pay additionally for SIM cards for the transmission operating system. Our estimation is based on high quality, proven instruments, which are also recognised as complying with government and international standards. A total indicative cost would be **€120,000.**

Installation costs of the instruments will vary, depending on site conditions and the volume of construction work necessary. If the site is already prepared for easy installation and a number of sites could be organised into rounds each day for the installation work then this could be about €460 per site. Where sites have more difficult access, or may require more time to be spent on secure installations, such as at river stations, installation costs could rise to €1,000-€1,200. Assuming straightforward installation at raingauge sites, and more extensive work at 50% of river sites, the indicative cost estimate for installations would be **€40,000**

There are a wide range of base receiver systems available, especially if receive-only capability is required. Some providers offer high end web-based servers which are free of charge for read only, but cost, say €40 per site per year if remote control of the data loggers is required for configuration purposes, which is considered to be highly advantageous. However, if the client wished to establish their own server, the following costs would apply: unlimited numbers connections for €5,000 with €1,000 commissioning and €3,000 for the hardware. Costs for consultancy and design are hard to specify, but would have to be included in the overall cost of design, build and installation. A minimum all-in cost of **€40,000** could be assumed for budget purposes. In recent applications the choice has been for providing a receiver that is capable of providing warnings based upon integrated rainfall intensities and levels, with a number of warning levels available from each out-station, with messages supplied by email and/or text message. This incurs a small charge (less than €50 for each block of 250 text messages). Only very basic training is needed to maintain such a network using this type of top-end equipment and allowance should be made for a cost of **€10,000** for 2-days training for a group of up to 20 people. However, as stated earlier, there may be reservations as to the resilience of email and text messaging within a critical warning system, so a decision should be taken at the design stage as to whether a more robust system should be used. A messaging and dissemination system as part of the data processing system is likely to add some **€150,000** to the cost of a central processing system.

It is assumed that the Primary Flood Forecasting and warning system required will be more sophisticated than the warning system above (which may suffice for certain CARs). To provide this, purchase of a model framework system, such as those used in flood warning undertakings in UK and Europe would be necessary. Consultancy costs to develop, install and test these systems would be significant, i.e. several hundreds of thousands of Euros. This would be a major cost, and could

only be ascertained when the system specification is more well defined. For preliminary budget purposes, a cost of **€250,000** could be assumed.

A major forecasting and warning system would also entail a range of annual operating costs. It would require such items as long battery life loggers and/or solar panels to minimise battery replacement costs, site servicing visits, which would be quarterly for river level sites and as frequently as fortnightly for raingauges. A cost allowance for this should be **€200,000.**

The flood forecasting system would also entail costs to receive the meteorological services. As the information items suggested will entail both development costs and then recurrent staff time, this again is not known. Meteorological services have separate rates of charging for data and forecast supply, and again, more specific detail will be required before an accurate cost could be defined. The provision of direct feeds of radar data would depend on arrangements with the meteorological service and whether simple transfer of radar scan images is requires or a more complex feed of digital data.

Table 3-D summarises the cost items above. It should be noted however that these cost items do not include operator staff costs and meteorological services and represent preliminary estimates that may vary greatly dependent on the sophistication of the system as described above.

Table 3-D Summary of Cost Items

Description	**Total Cost (€k)**
Raingauges and water level recorders (purchase)	120
Instrumentation installation costs	40
Base receiver systems – consultancy and design	40
Training	10
Messaging and dissemination system	150
Primary flood forecasting and warning system	250
TOTAL	**610**
Annual operating costs	200

3.3 Consideration of content and targeting of warning messages

The expectation of flood forecasting and warning provision from professional partners, communities and the public has increased over recent years, reflecting the increased losses incurred from flooding and the level of disruption to everyday life. It is therefore highly important for connectivity between all parties, from the provision of advanced cautionary information, to effective response to the event.

In a major system like the Shannon in Unit of Management 25/26 with mostly slow responding rivers, flood warnings will largely be related to river levels, and need to relate to progressively increasing significant stages or triggers, e.g.:

1. Level at which water flows out of channel onto the floodplain;
2. Level of water which submerges areas of land used by livestock, or low lying roads become flooded;
3. Level where major areas, including residential and business properties, and communications are affected;

4. Level where the combination of depth and velocity in flooded areas pose a threat of structural damage and danger of loss of life.

The general arrangement for flood warning stages is illustrated in Figure 3.3. A schematic of the forecast and warning relationship from rainfall forecast to downgrading of a warning is illustrated in Figure 3.4[15]. Triggers will need to be carefully selected as part of the detailed design of the forecast model and warning arrangements, which should be based on the following stages.

- Early advice as to the possible occurrence of weather conditions conducive to flooding – this is primarily the function of the meteorological service;
- Identification of the development of critical conditions, such as saturated catchments and forecast of significant rainfall – this should be the stage at which preparations for implementing the flood-forecasting operations take place, and may be referred to as a flood-watch;
- Alert stages that identify a clear and developing threat of flooding, due to the actual and forecast rainfall and catchment conditions – this is a situation in which flood-forecasting capacities operate;
- Increased detail on timing, extent and magnitude of flooding in the immediate future, hours rather than days – this constitutes flood warning, which is the stage during which response preparations need to be completed;
- Updates and revisions to flood warnings as situations develop, which will form part of the decision-making response and implementation of remedial actions – this stage should allow for enhanced warning, as a severe flood warning or identification of an emergency situation;
- Identification that the situation regarding a combination of weather forecasts, rainfall and river condition point to an improvement in the situation such that a downgrading or all clear statement can be issued.

It must be emphasised that forecasts and warnings should not be treated as a one-off statement in a proscriptive fashion. Forecasts and warnings are progressive. Taking as an example the lower Suck and Callows area, the event analysis has shown an extended lead-time exists from commencement of river rise to the time of a major peak, in the order of 3 or more days. This is of the same time frame or longer as the initial routine severe weather alert/forecast, which is 2-3 days. Thus forecasts and warnings need to be considered in a decision support context. If the river starts to rise from an already high level, **and** an early warning of heavy rain is received, **and** a subsequent quantitative precipitation forecast for 24-36 hours above a selected threshold is received, **and** river rise approaches a local trigger, then the issue of flood warning with a lead time of 18-24 hours is possible.

[15] Manual on Flood Forecasting and Warning. WMO, Geneva, in press

Figure 3.3 Arrangement of Trigger Levels for various flood warning stages

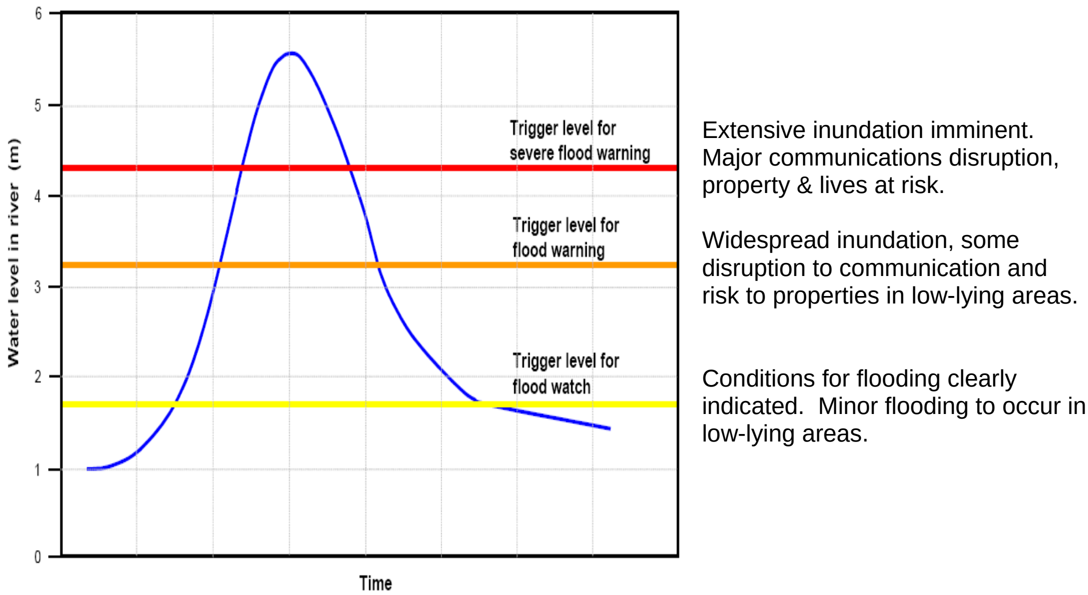
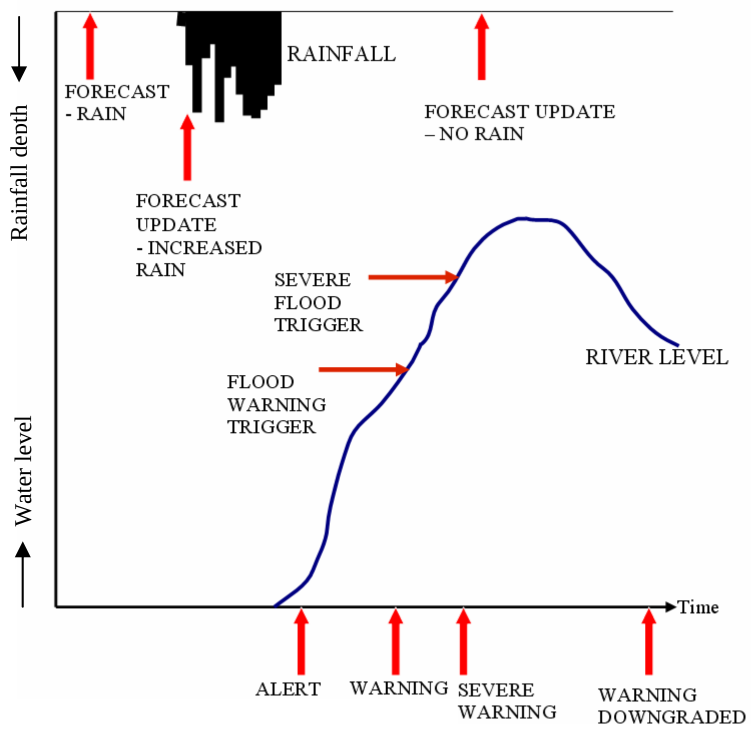


Figure 3.4 Flood Forecasting and Warning Schematic



3.3.1 Routine Forecasts and Early Advisory

Initial identification of adverse conditions could come from two sources, the European Flood Awareness System (EFAS) and Met Éireann 6-day forecasts. Both these have origins in medium range weather forecasts (8-10 days) based on available numerical weather prediction models, so should be consistent with one another. The EFAS forecasts are of a general nature, and being prepared for a range of catchments across Europe, may lack the definition to be of real benefit.

It is suggested that early advisory information is prepared as a daily routine by the meteorological service, covering information on soil moisture deficit and rainfall quantity, focussed on the four basin areas given in 3.2.1. The information would come as a daily bulletin issued at a fixed time, giving:

1. Latest SMD values for 3 soil classifications;
2. Graphical and tabular forecast of rainfall over the current and next 5 days. Information should be given for days 1 at 6-hour intervals, days 2 to 3 at 12-hour intervals, and for days 4 to 6 as a daily estimate.

This type of daily forecast is an essential part of a flood forecasting and warning operation. It will not contain any specific warning messages, but would act as a means for the responsible organisations to understand the general conditions, but not involve any onward transmission of messages.

3.3.2 Flood Watch

A flood watch aims to prompt the first stage of activating flood forecast and warning procedures, and would be issued when a potential flood incident is developing. It may be announced for a single or groups of flood warning units, and would be a decision taken by the responsible organisation from a combination of pre-defined triggers from monitored and forecast data.

The data would comprise forecast rainfall over the next 3-5 days which contains one or more forecast period includes a rainfall estimate higher than a trigger. These will refer to standard forecast time blocks as for the routine rainfall forecasts. Those receiving the forecasts should be alert to the fact that although a single forecast period may not exceed the threshold, two successive periods might suggest that a trigger quantity could be exceeded. For example, if 30mm of rainfall in 24 hours is a chosen threshold, and two 24-hour blocks (00z-24z) have forecasts of 15mm and 25mm, it is possible that a total rainfall in excess of 30mm could occur in an actual period of 24 hours or less.

Other variables to be taken into consideration in the decision making process would be:

- River levels at or approaching a trigger level defined to give early indication of a significant flood;
- SMD values at or near zero;
- Cumulative rainfall, e.g. as a 5-day running mean, reaching pre-established thresholds at reference rainfall stations.

Once Flood Watch status is achieved, standard text warnings should be issued to a pre-determined set of organisations involved in flood response. A general public notice should also be issued through the media, e.g. in normal news and weather forecast bulletins and through the Internet.

3.3.3 Alert

An alert status should be announced when the conditions that led to the Flood Watch have advanced to more critical levels. The most likely cause would be a more definitive forecast of heavy rain over one or more sub-daily periods and a continued observed or forecast rise in reference river levels above a level above which flooding is imminent. In the case of the sub-divisions of Unit of Management 25/26, this would be possible 1 to 2 days ahead. The Alert status message should

be sent to all responders, including emergency services, and should be the key to their making specific flood response preparations, e.g. preparation of supplies of sandbags at depots, preparation to mobilise road closure notices, and direct warning to high risk areas.

3.3.4 Flood Warning

Flood warnings should be issued when disruptive flooding is imminent. The exact conditions and timing for the issue of flood warnings are not proscriptive, but depend on the nature of the catchments and at-risk sites concerned. Usually the triggers are:

- *Early stages of flooding being reported;*
- *Heavy rainfall conditions are forecast for the immediate future, or have been identified as occurring over the catchment by telemetry raingauges and/or radar;*
- *River levels at at-risk sites are reaching critical levels;*
- *River forecasts indicate that river levels will continue to rise.*

The most important requirement for flood forecasts are that they give sufficient lead time for control and management procedures to be put in place, e.g. sand-bagging of property and river defence structures, closure of flooded roads, moving personal belongings above known flood levels. The actual provision of lead-time is variable. In urban areas 2 to 3 hours is usually considered desirable, and should be the target for APSRs where immediate river levels are of importance. In remote areas, such as the Shannon Callows, several hours may be needed to reach animals and move them to safer sites.

The organisation responsible for the warning will need to develop messages in an agreed format to convey warnings with sufficient precision to professional partners, emergency responders and the public. Special provision should be made for warnings to be issued using public media, the Internet and designated direct warning services.

3.3.5 Severe flood warning and emergency

A severe flood warning would follow on from an existing flood warning when conditions continue to deteriorate. This would have been the case in the situations of the three historic floods which were examined, and possibly one or two other recorded events. These cases all resulted from a sequence of heavy rainfall events following closely on one another, and would be identified from updated rainfall forecasts, observations of increasing rainfall and river level and subsequent model updates. The type of rainfall forecasts required would be similar to “flash” warnings already provided by Met Éireann, which cover periods of a few hours’ duration with a short lead-time. These forecasts are issued on the basis of information from radar and model nowcasting on the judgement of the duty forecaster, but would require considerable effort to convert into a suitable form for transmission and ingestion into a real-time flood model.

A severe weather warning entails the updating of the earlier flood warning and an escalation of the response actions. In the most serious cases, this may require the involvement of immediate rescue and evacuation involving defence forces. Other actions may involve direct messages to the public through wardens, interruptions for media warnings, sirens, etc.

3.3.6 All-clear

The “all-clear” status is as important a part of the flood warning process as the build-up stages. It is more directly linked to river model forecasts, but is also dependent on the meteorological forecasts indicating that no significant rainfall is expected. In our experience with other flood forecast operations (UK, Bangladesh), cases have occurred that although the river forecast fell below the warning trigger level, the all-clear status was not announced as rainfall forecasts indicated subsequent increase in flows might occur. The all-clear status is useful to both professional partners, in that it indicates a standing-down of response activities can commence, and where evacuation has been required, that it could be safe to return home.

4 Conclusions

The study has examined the nature of floods in general and on specific "at-risk" sites, defined by OPW as Areas of Potential Significant Risk (APSRs). The existing hydrometric and raingauge networks have been compared with hydrological characteristics of Unit of Management 25/26, and with the representativeness of instruments compared to the locations of APSRs.

Particular attention has been given to the behaviour of major flood events, in 1999, 2008 and 2009. These were serious events and caused widespread and disruptive flooding, as well as affecting many of the APSRs. The extent and magnitude of flooding in some places included maximum historical values, and understanding the detail of the hydrometeorology of these floods has provided the key to requirements for flood forecasting. Some localised flooding at individual APSRs was also investigated, and these mostly appear to be the result of isolated summer rainfall events. Trends of historic rainfall and variation, and probability of flooding have also been examined, with the conclusion that although no discernable future climate "signals" can be identified, it can be expected that flood events, large and small, will continue to be a cause of problems.

The present flood forecasting arrangements and heavy rainfall warnings would be insufficient to deal with the level of warning now expected, when similar events occur in future. The basis of a new system would require much greater automation in monitoring and improved use of early alerts from forecasts and catchment states. The requirements of both general catchment wide flood forecasts, and localised forecast/warning for APSR sites has been examined, and it is suggested that a two-tier system of flood forecasting could provide an effective solution. The primary system would operate on a catchment basis with direct communication (telemetry) from 15 raingauges and 18 river gauges. Except for one new river gauge, all these instruments would operate from existing OPW, Local Authority and Met Éireann measurement stations. A secondary system, located in more direct proximity to APSRs would require the automation of 8 raingauges from existing sites and 12 river gauges. One additional raingauge and up to 4 river gauges would be required.

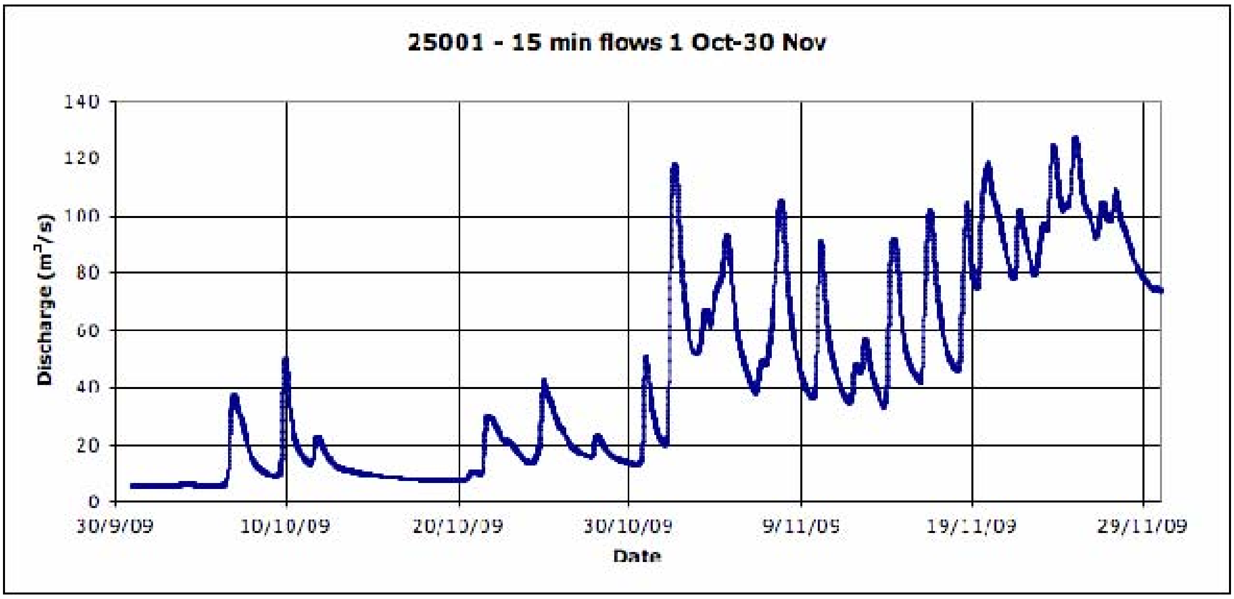
The closer monitoring of catchment conditions, to include soil moisture deficit and antecedent rainfall, would greatly assist early awareness and preparedness for flooding. In addition, more specific forecasts and warnings of the distribution and quantity of rainfall would be an aid to response preparation. Use of such data as ancillary information, or as direct data feeds into any modelling system, would provide flood forecasts on a catchment basis. These could be applied to many of the APSRs, whilst other sites would benefit form localised monitoring and automatic triggering of forecasts/warnings, once defined thresholds were exceeded. Some suggestions have also been made with regard to the type of flood warnings for professional partners and the public that could be developed from the forecasting system.

Some approximate preliminary costings have been provided, but it is emphasised that a more detailed plan for the observation, communications and modelling provisions would have to be made before the full cost of a system could be estimated. Costs and inputs would also need to be compared with benefits that might accrue from a forecasting system.

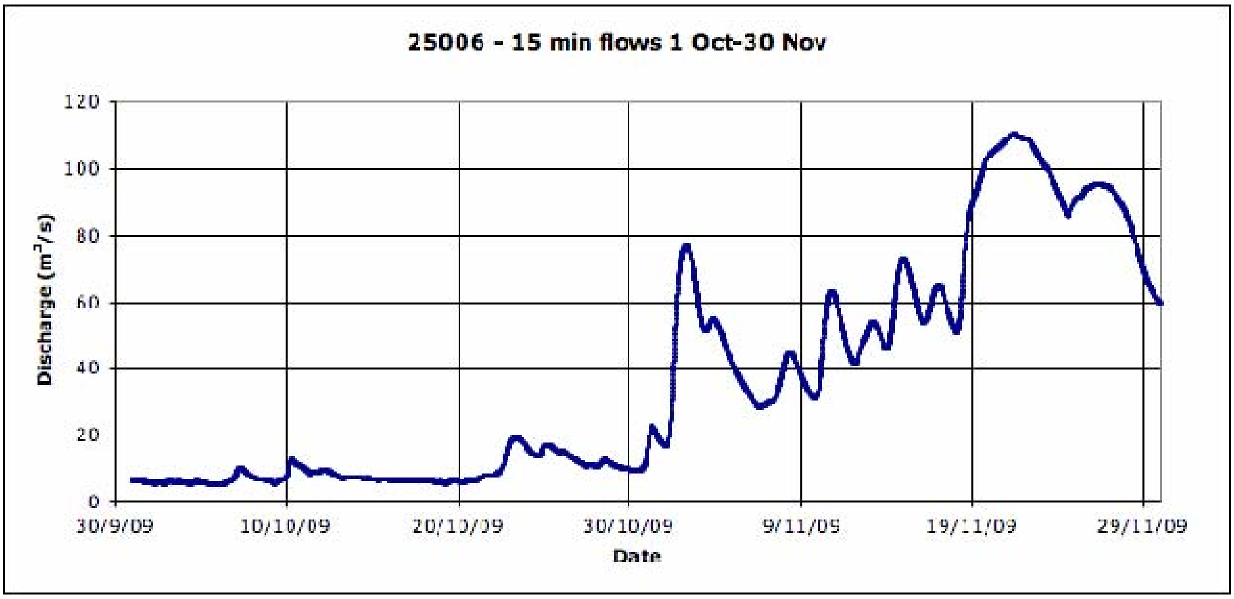
Appendix A - Flood Event Data Graphs, October - November 2009

Figures A.1 (a – d) Typical Hydrographs

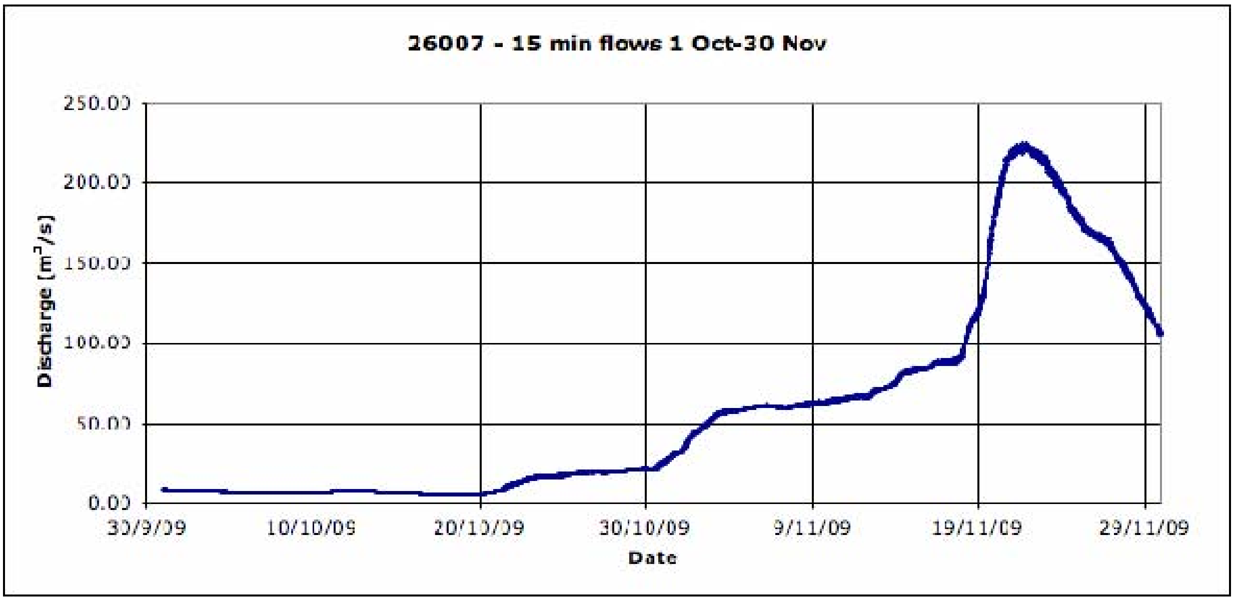
A.1a River Annacotty at Mulkear



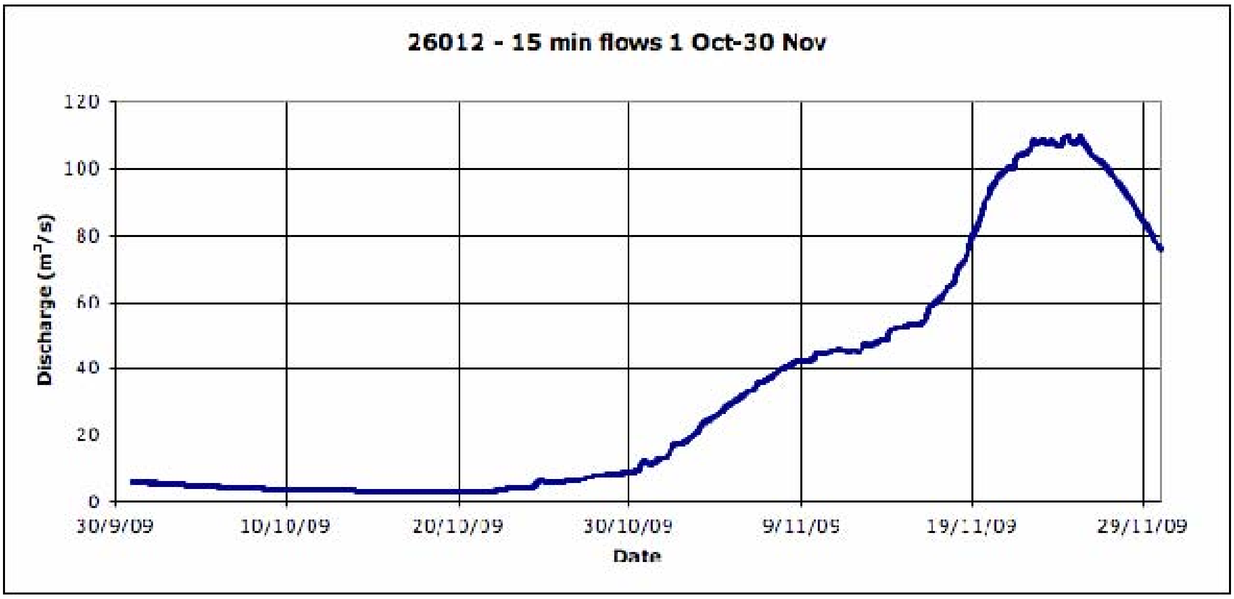
A.1b River Brosna at Ferbane



A.1c River Suck at Bellagill

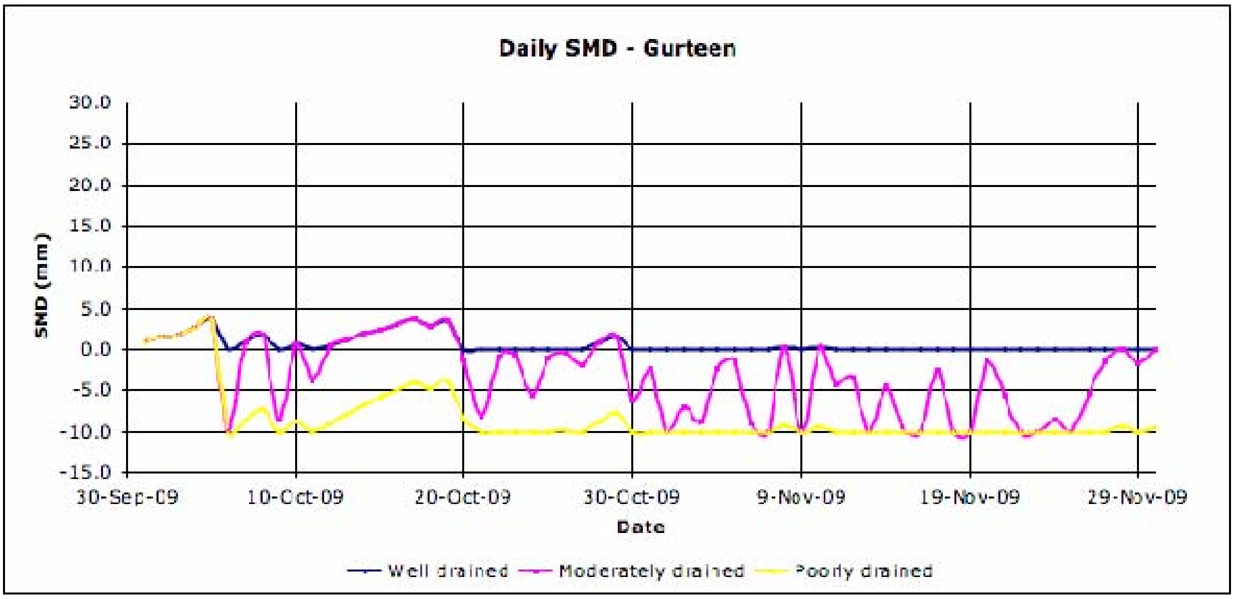


A.1d River Boyle at Tinacarra

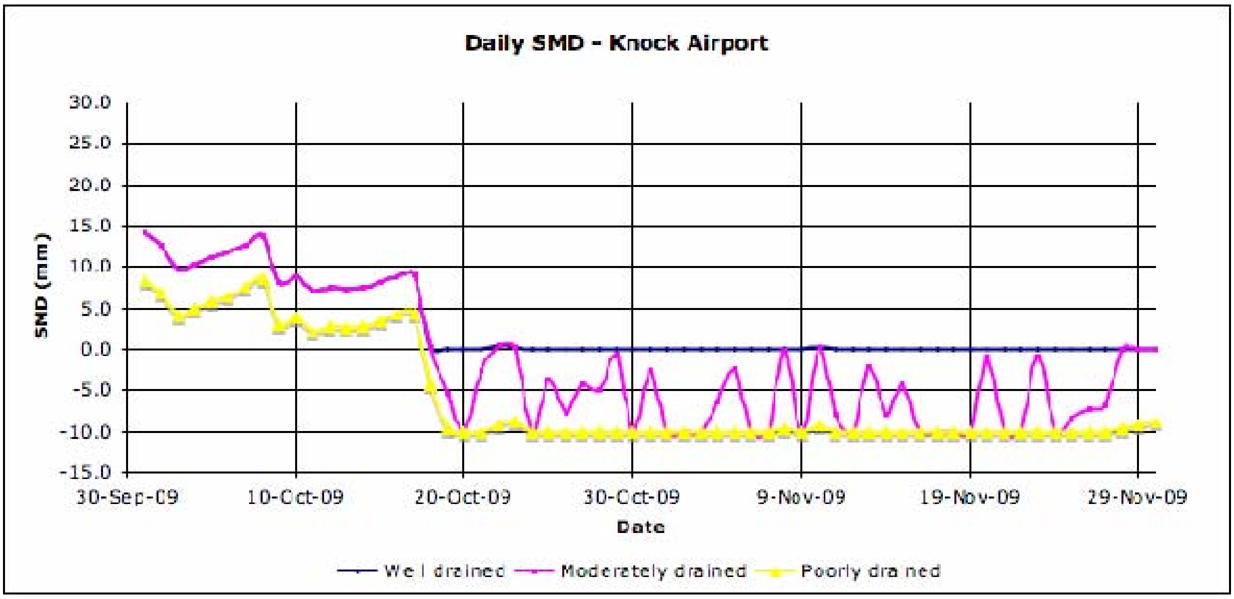


Figures A.2 (a – d) Soil Moisture Deficit Observations

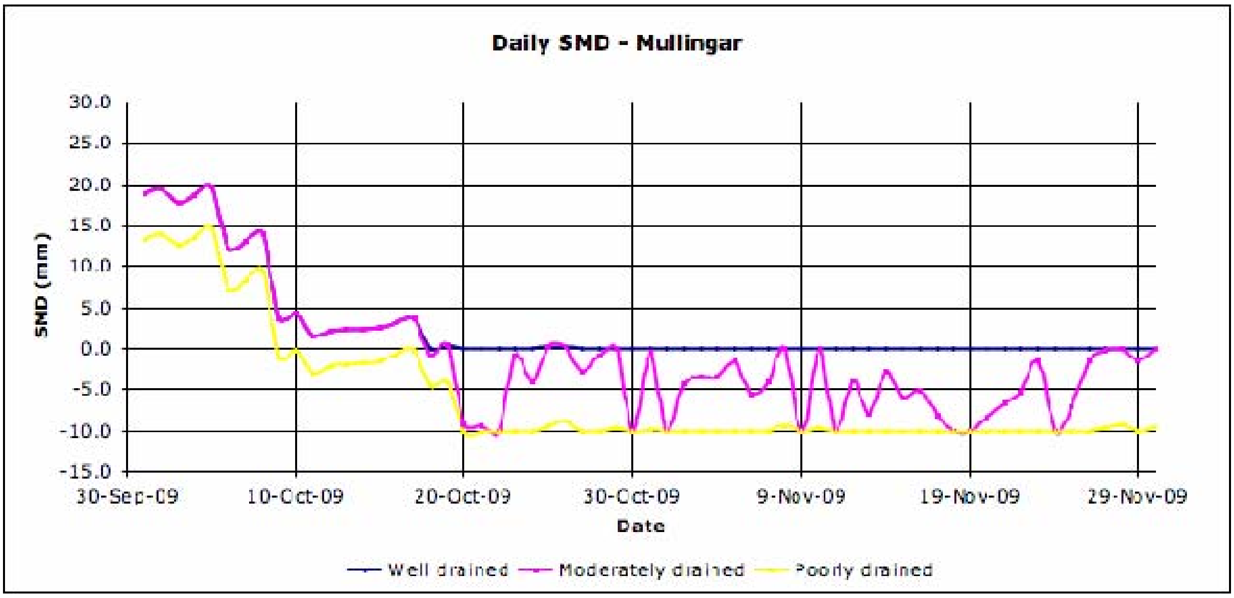
A.2a Gurteen



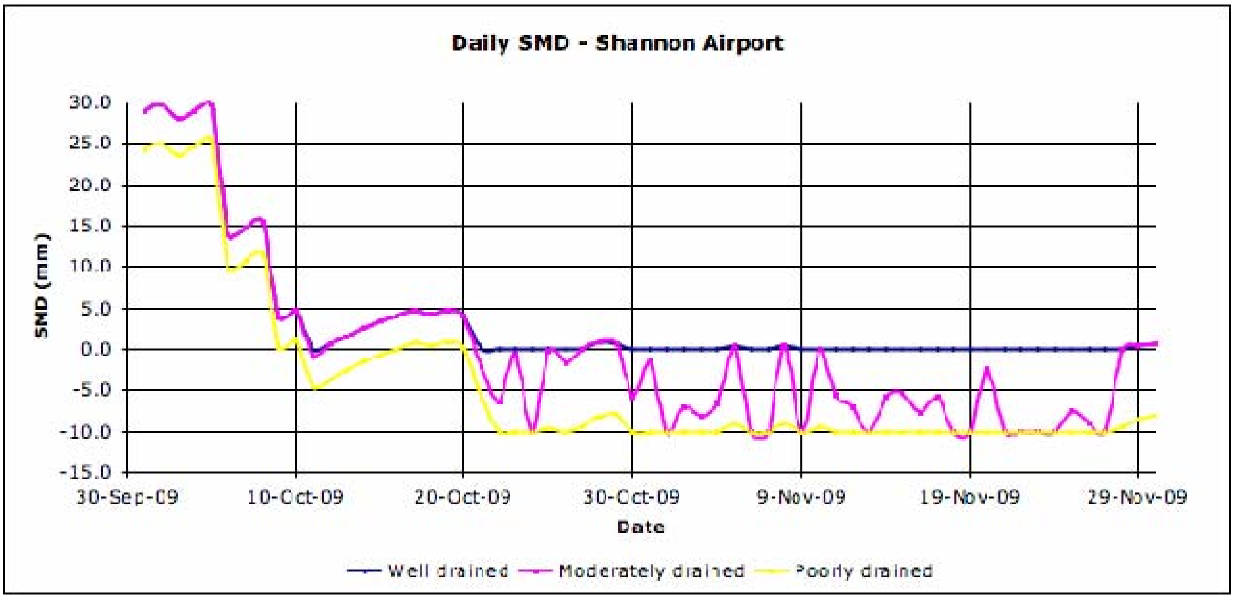
A.2b Knock Airport



A.2c Mullingar

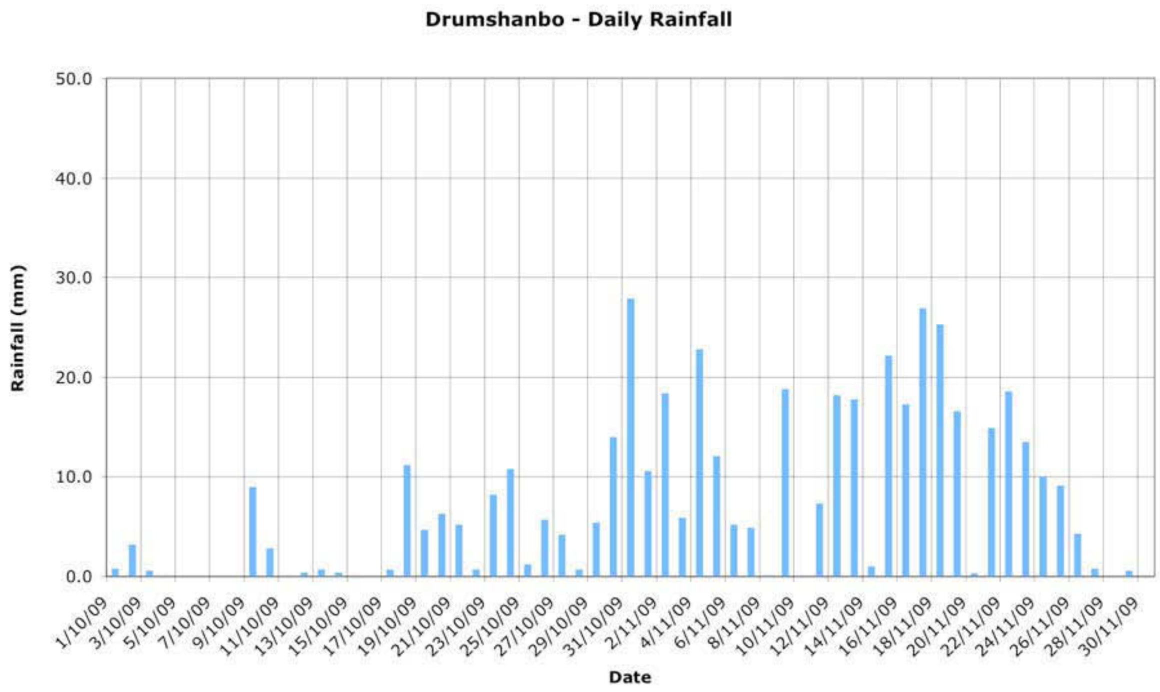


A.2d Shannon Airport

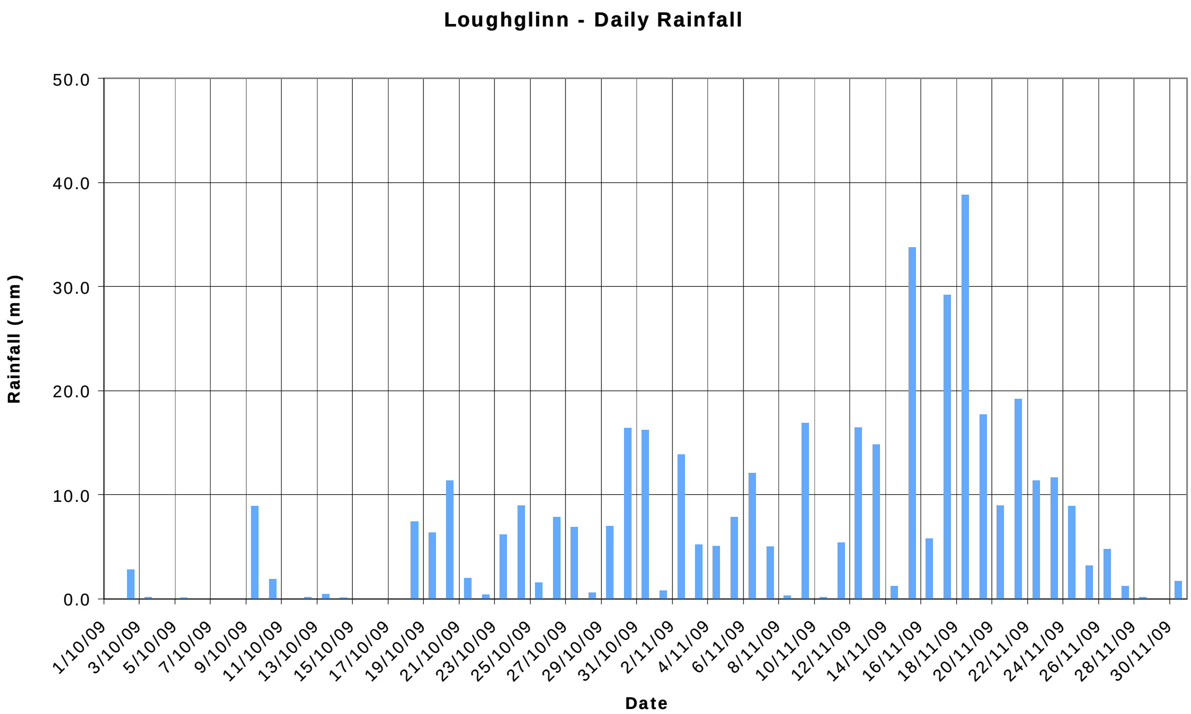


Figures A.3 (a – h) Sample hyetographs of daily rainfall

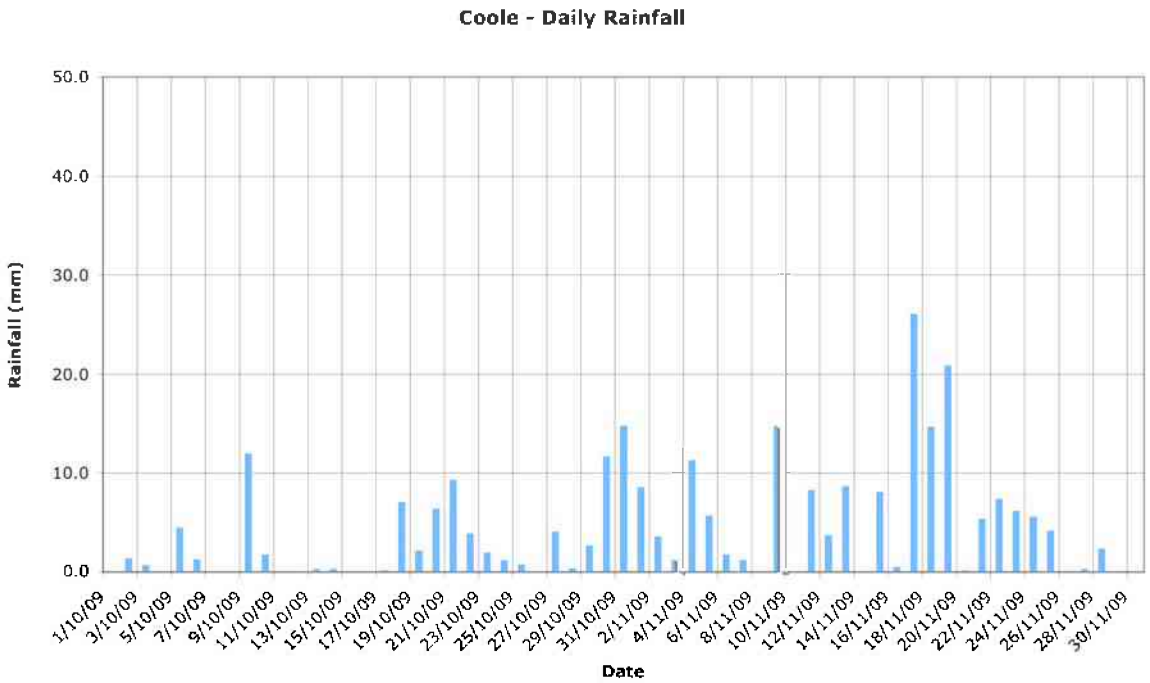
A.3a Drumshanbo



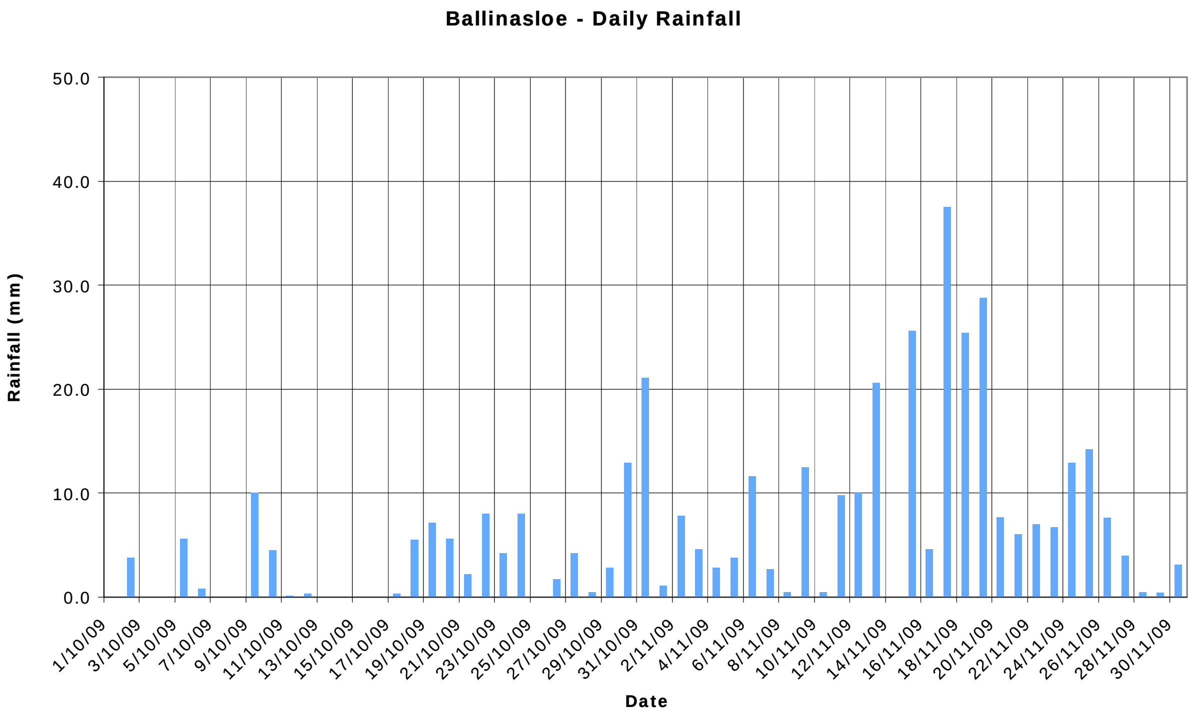
A.3b Loughglinn



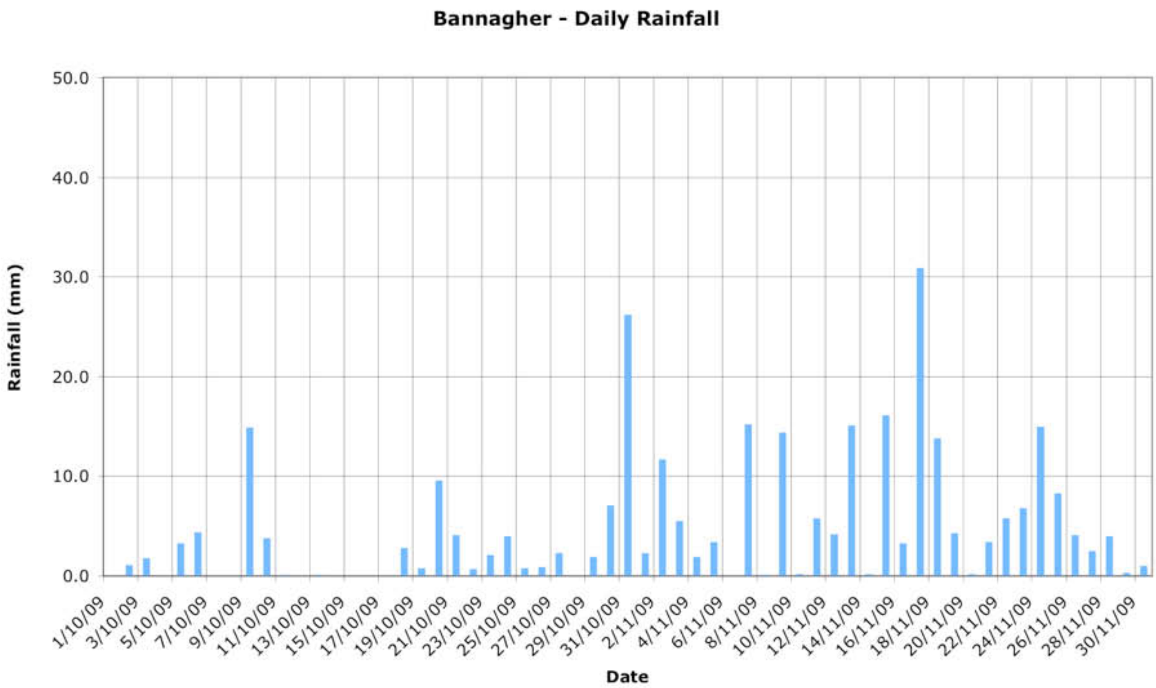
A.3c Coole



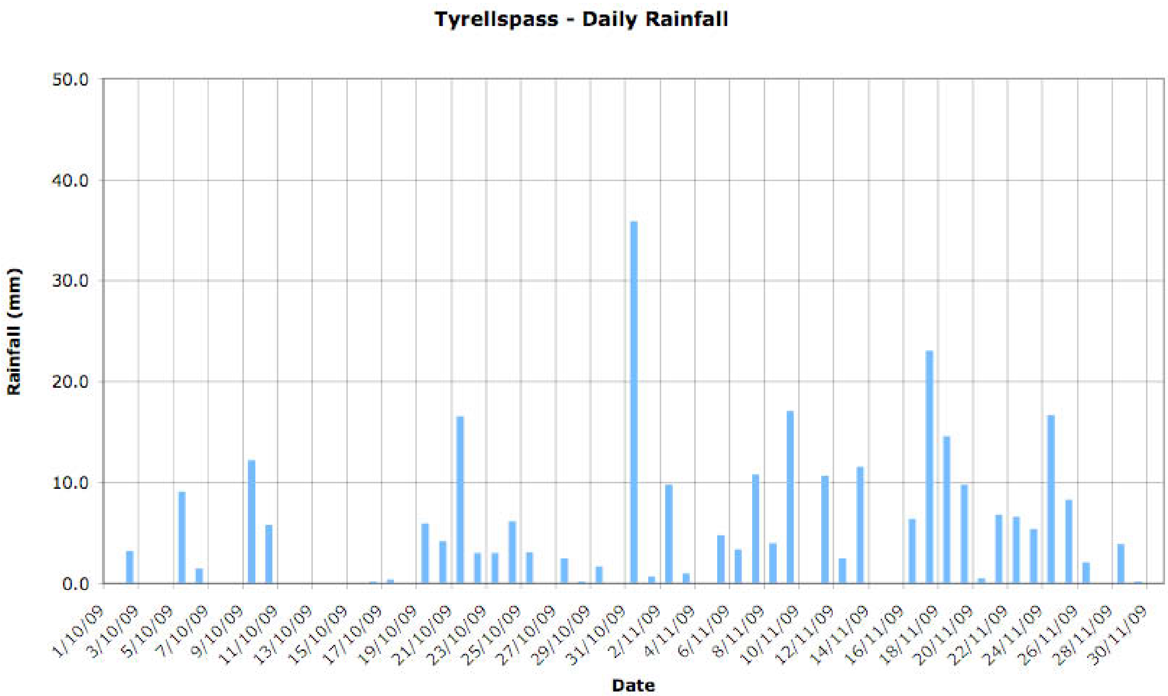
A.3d Ballinasloe



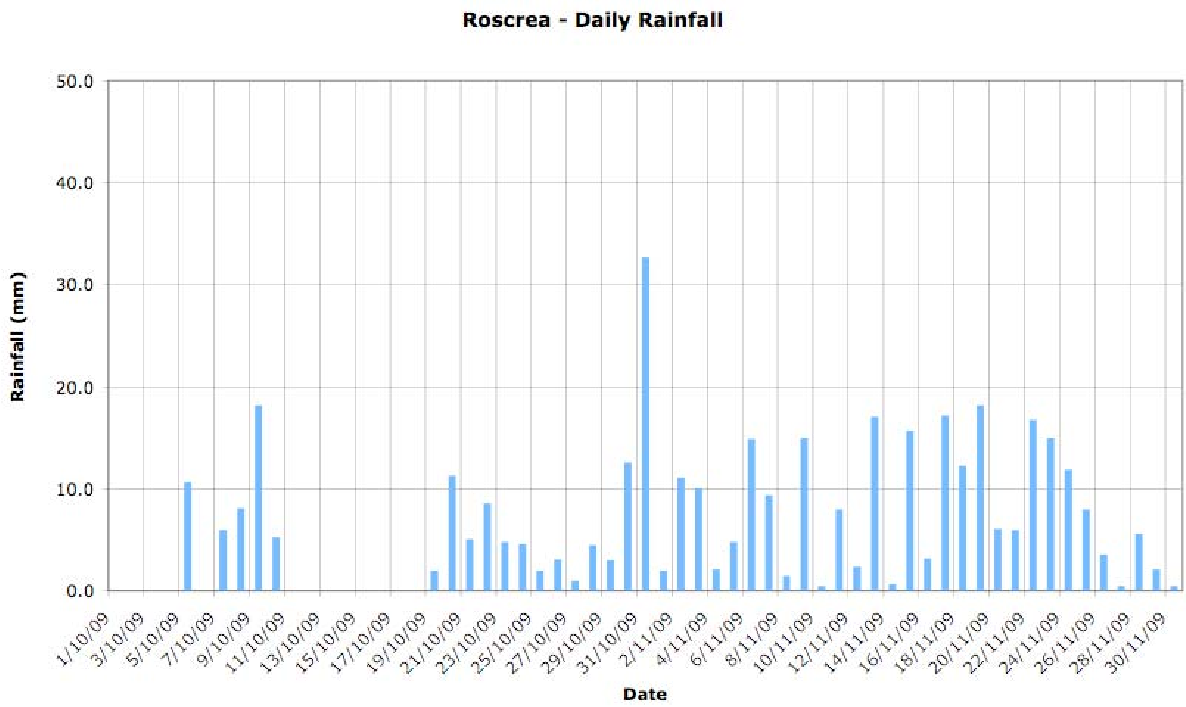
A.3e Bannagher



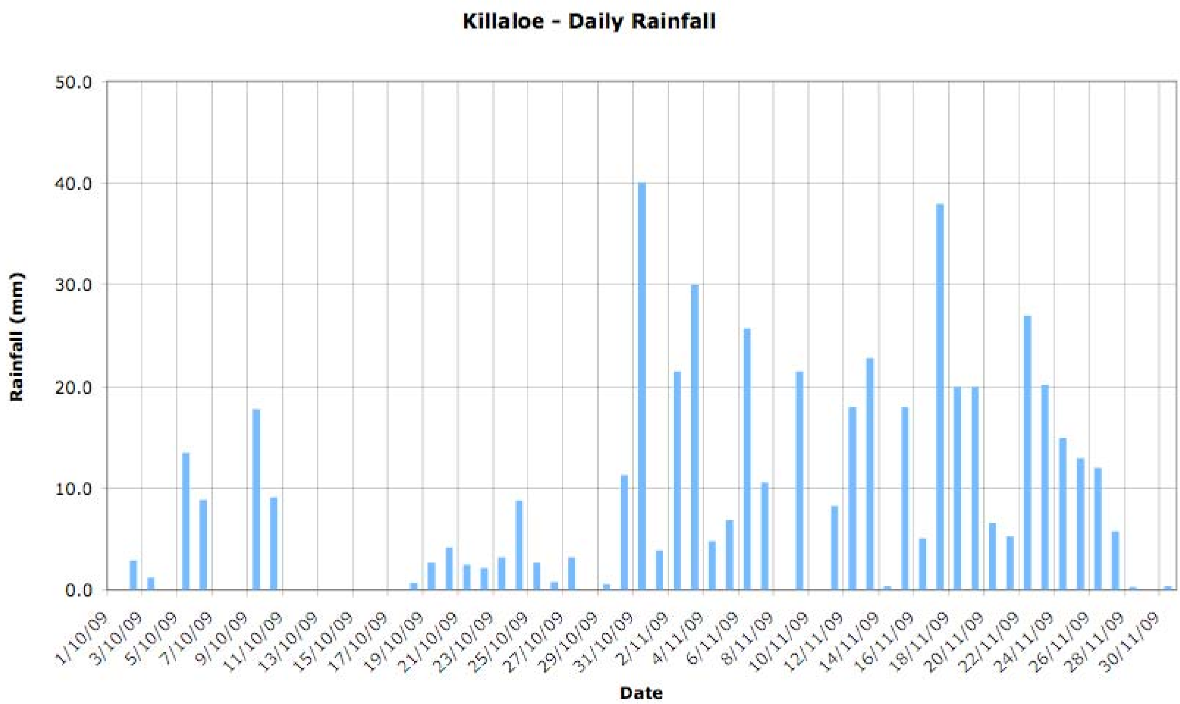
A.3f Tyrellspass



A.3g Roscrea



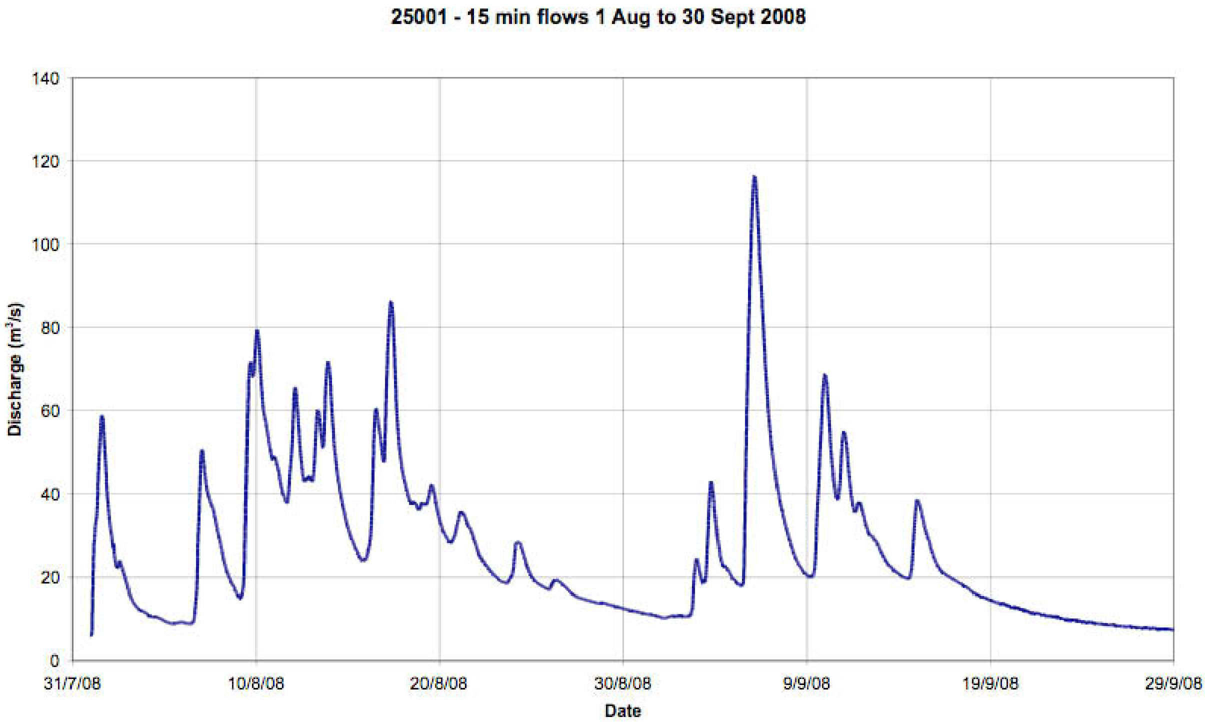
A.3h Killaloe



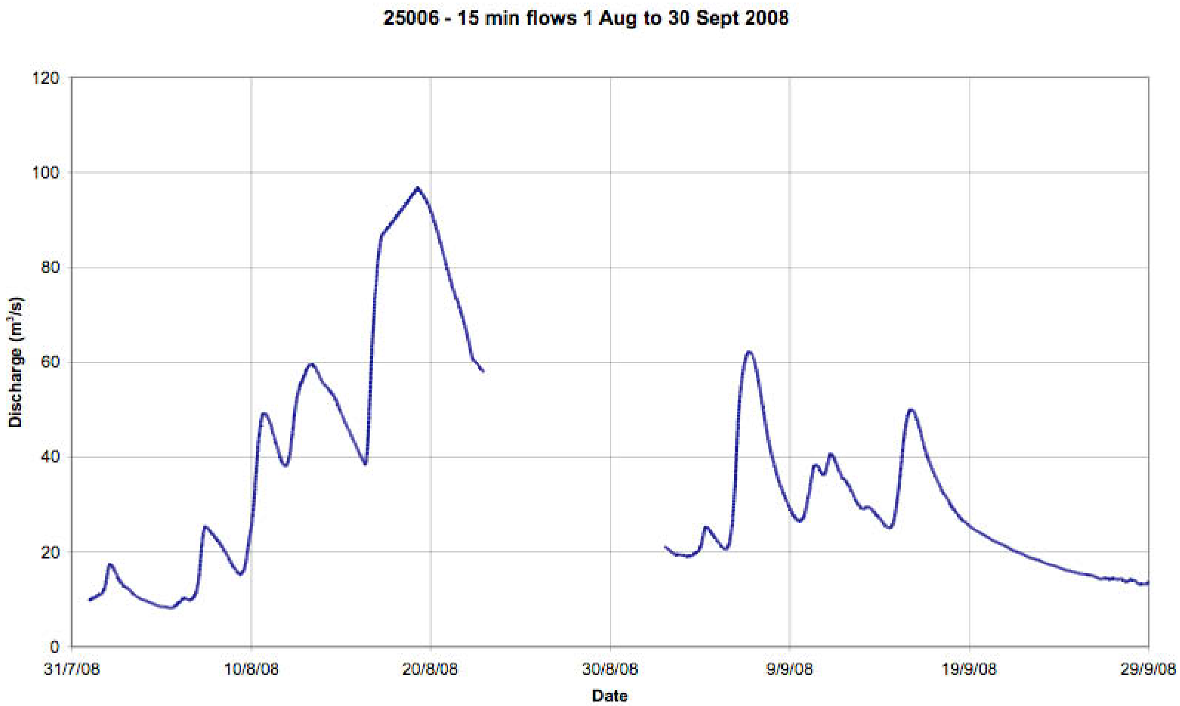
Appendix B   Flood Event Data Graphs, August - September 2008

Figures B.1 (a – d) Typical Hydrographs

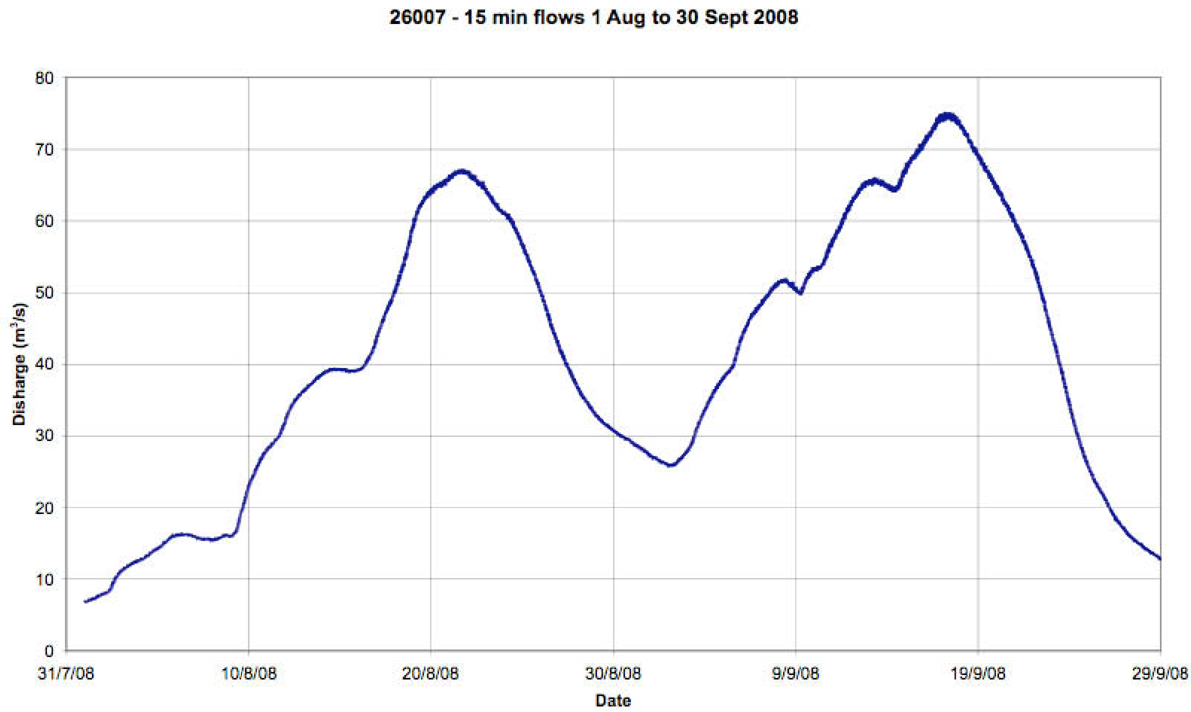
B.1a River Annacotty at Mulkear



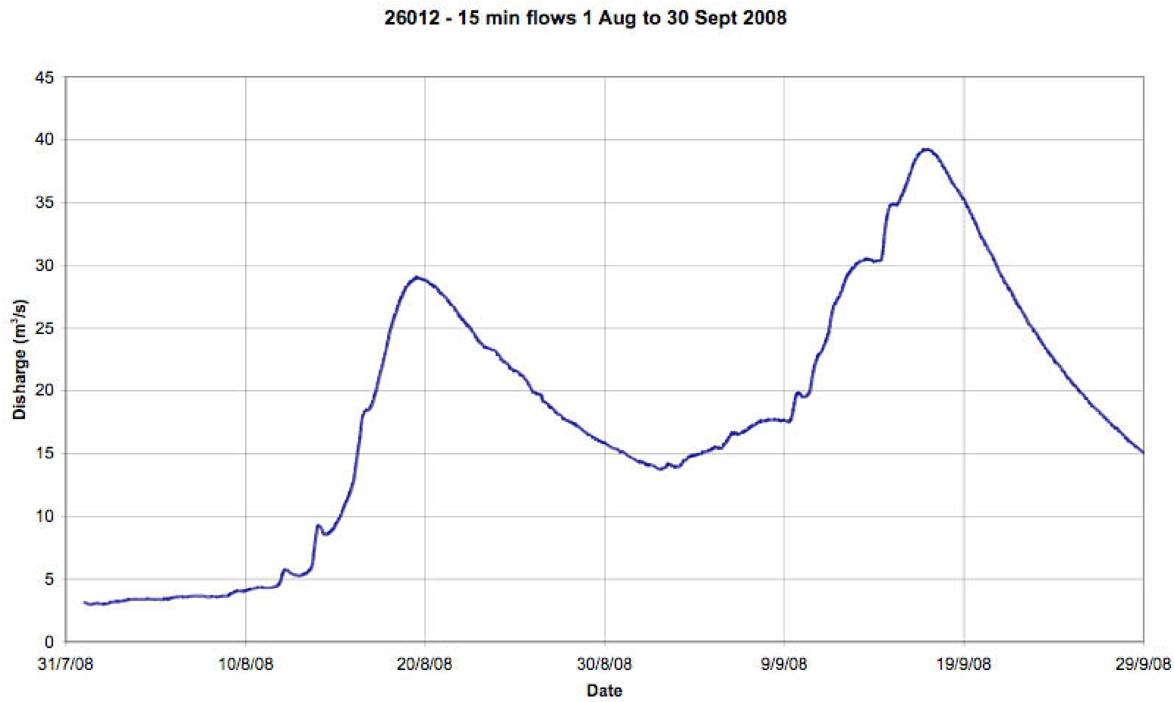
B.1b River Brosna at Ferbane



B.1c River Suck at Bellagill

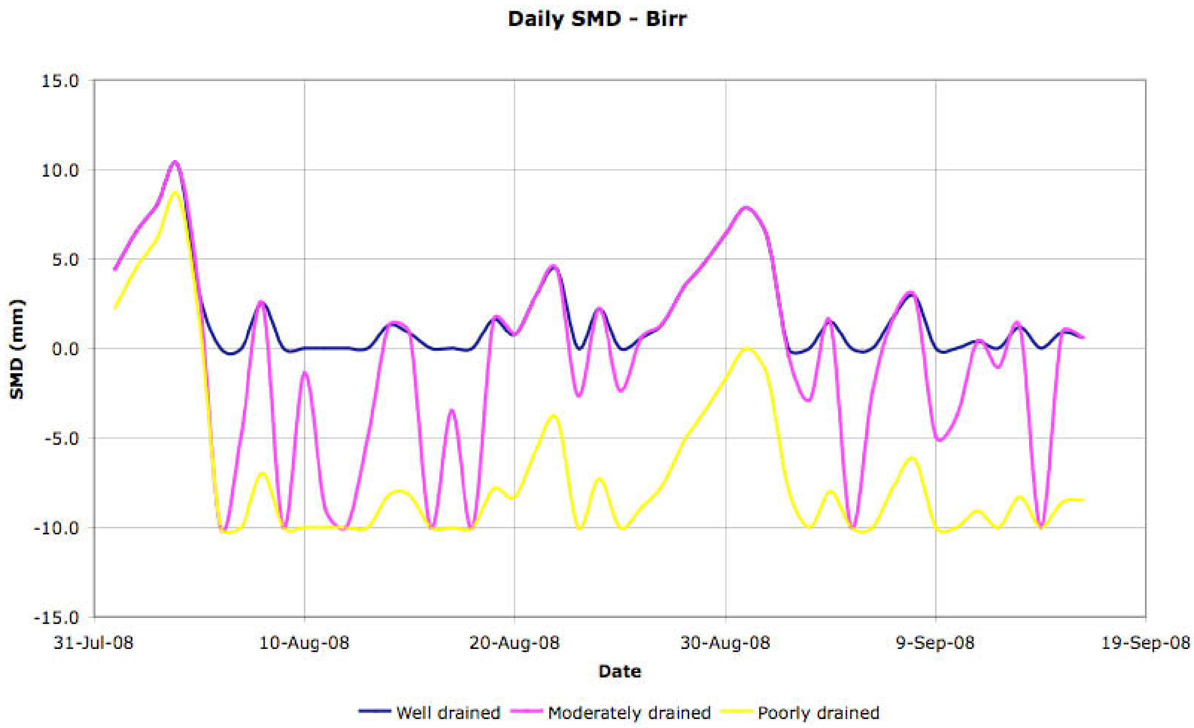


B.1d River Boyle at Tinacarra

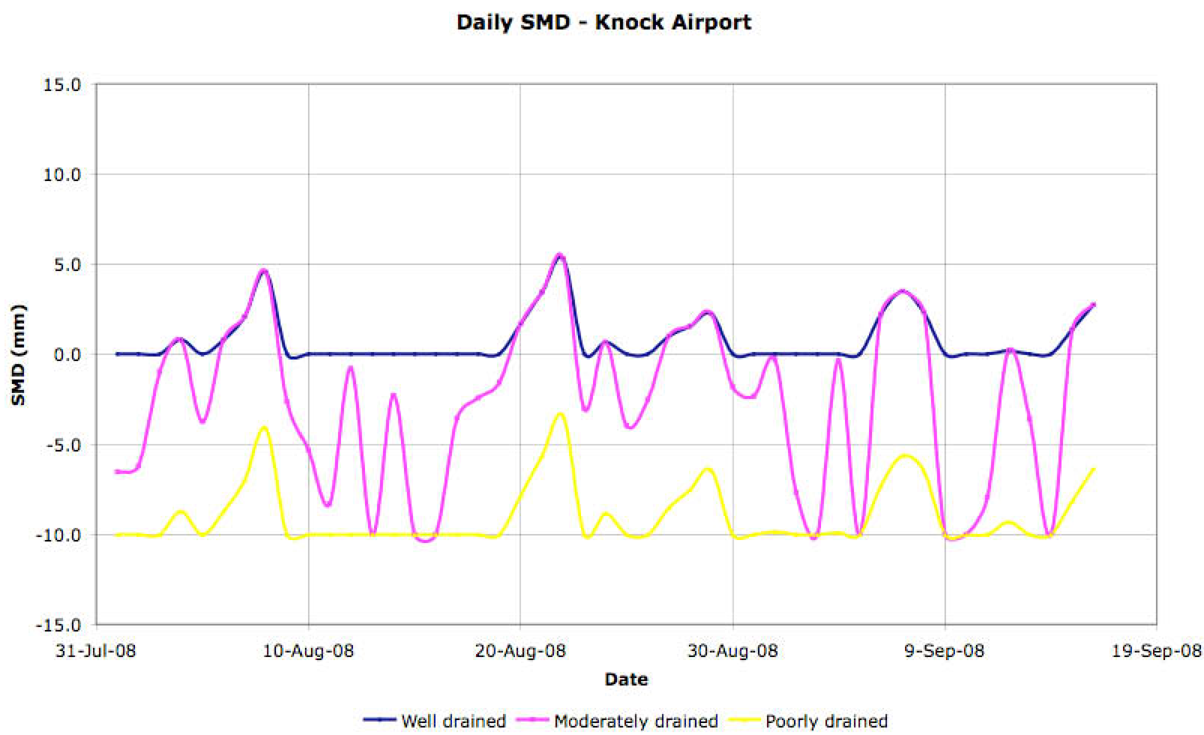


Figures B.2 (a – d) Soil Moisture Deficit Observations

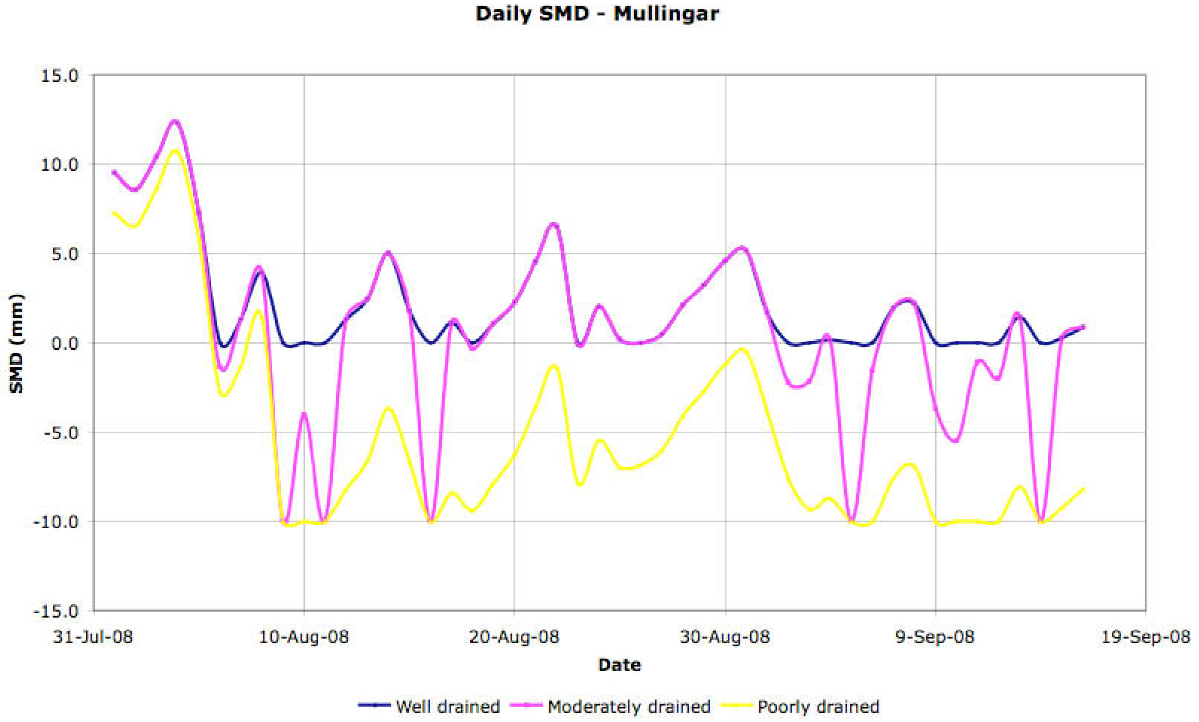
B.2a Birr



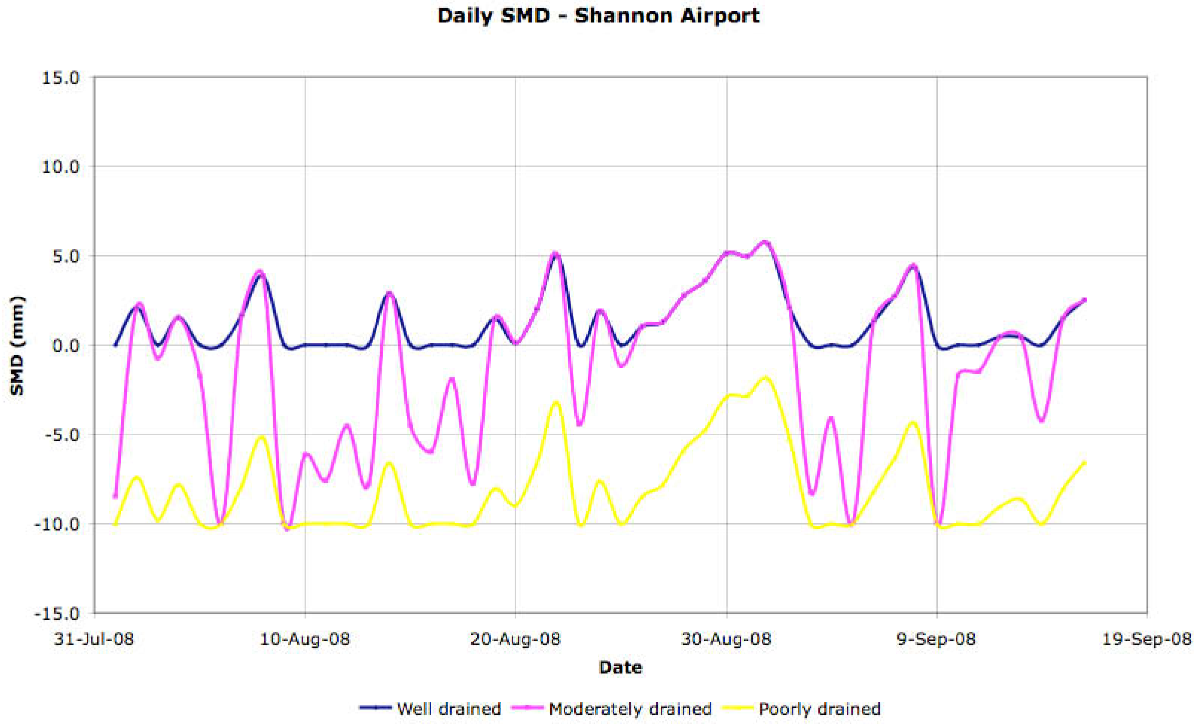
B.2b Knock Airport



B.2c Mullingar

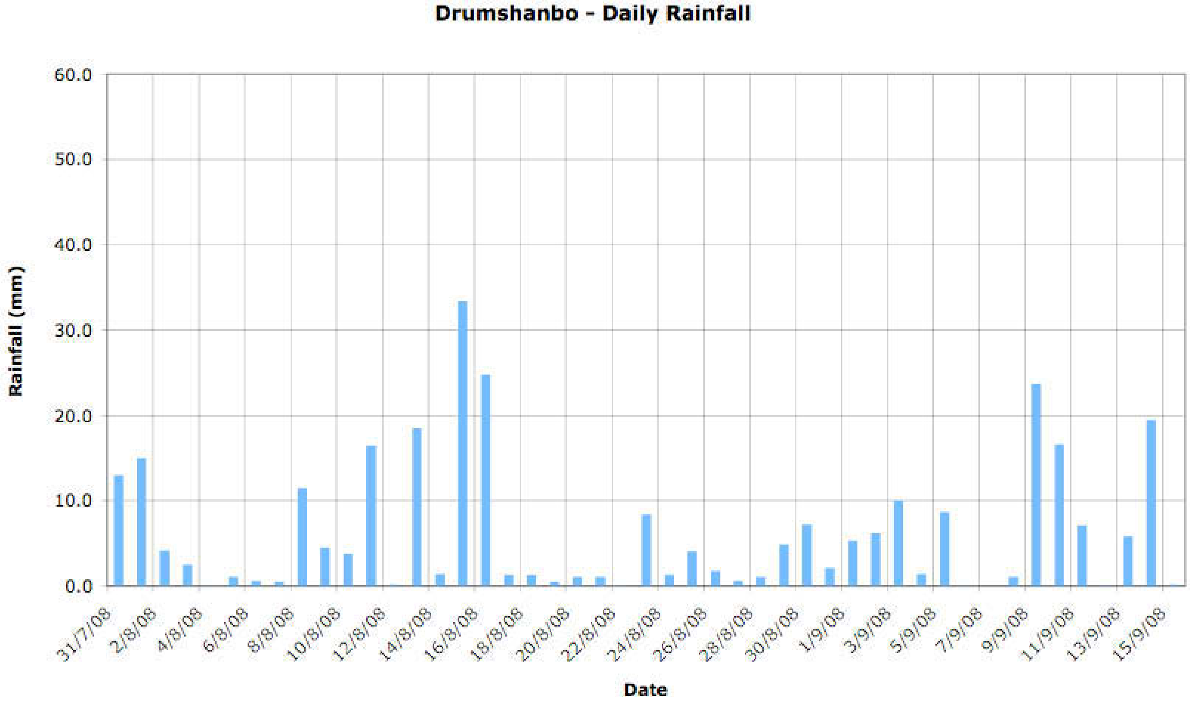


B.2d Shannon Airport

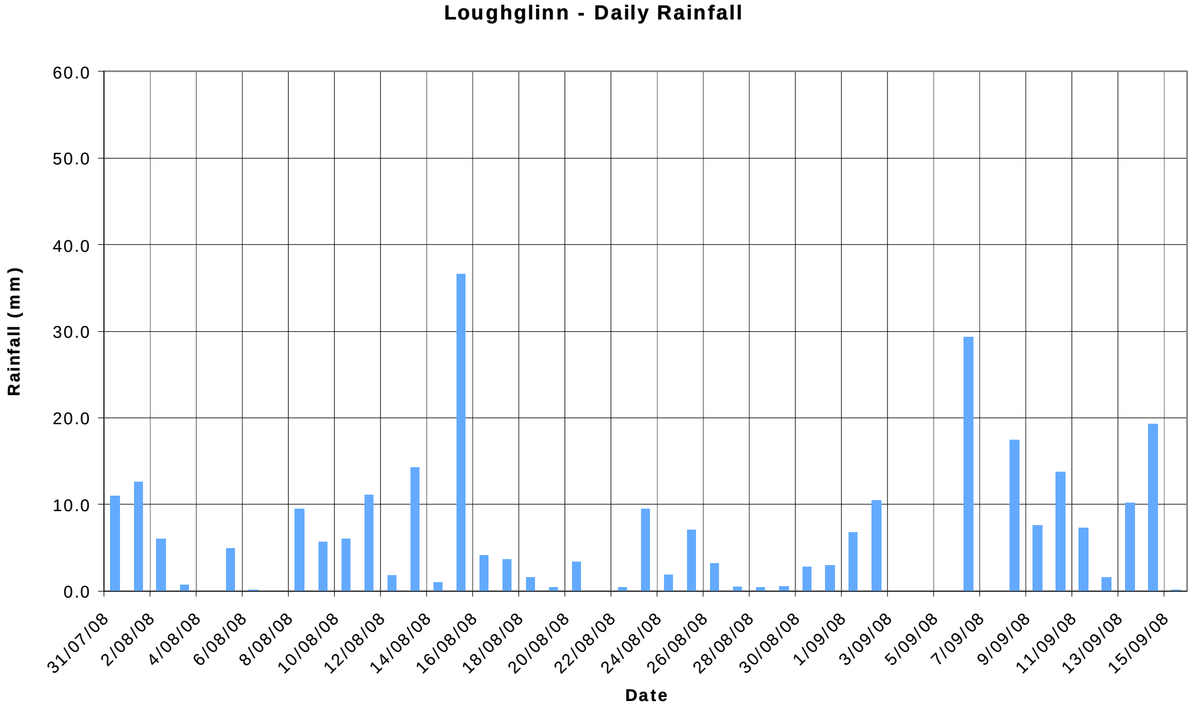


Figures B.3 (a – h) Sample hyetographs of daily rainfall

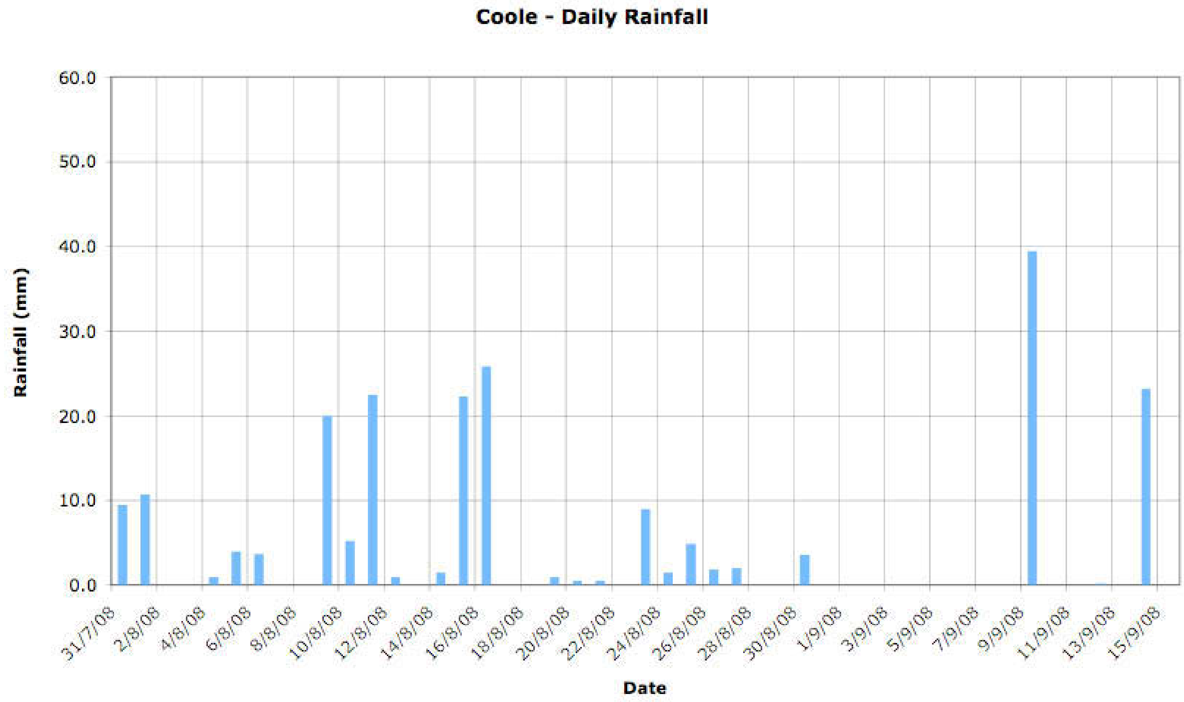
B.3a Drumshanbo



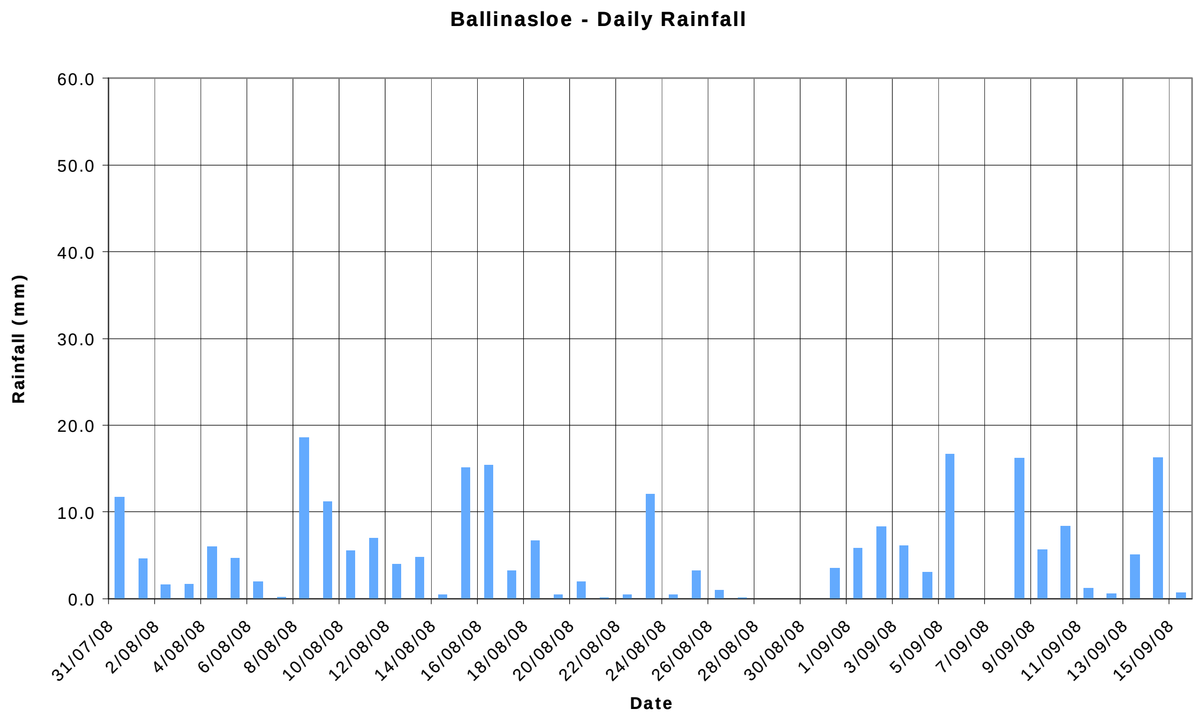
B.3b Loughglinn



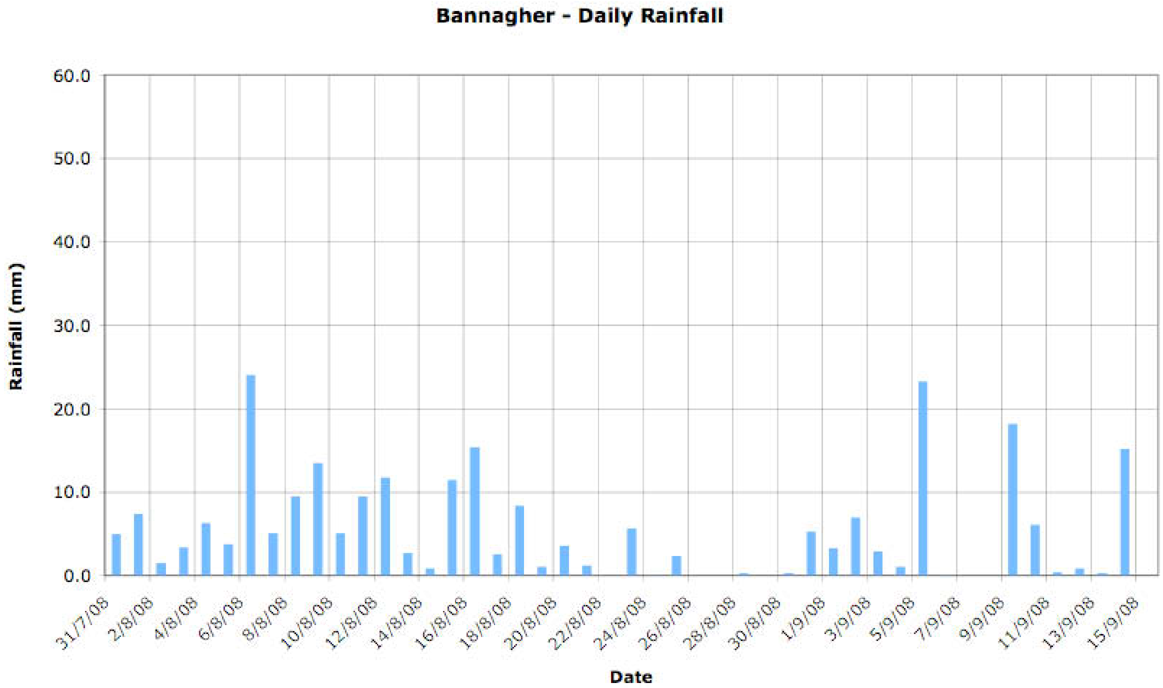
B.3c Coole



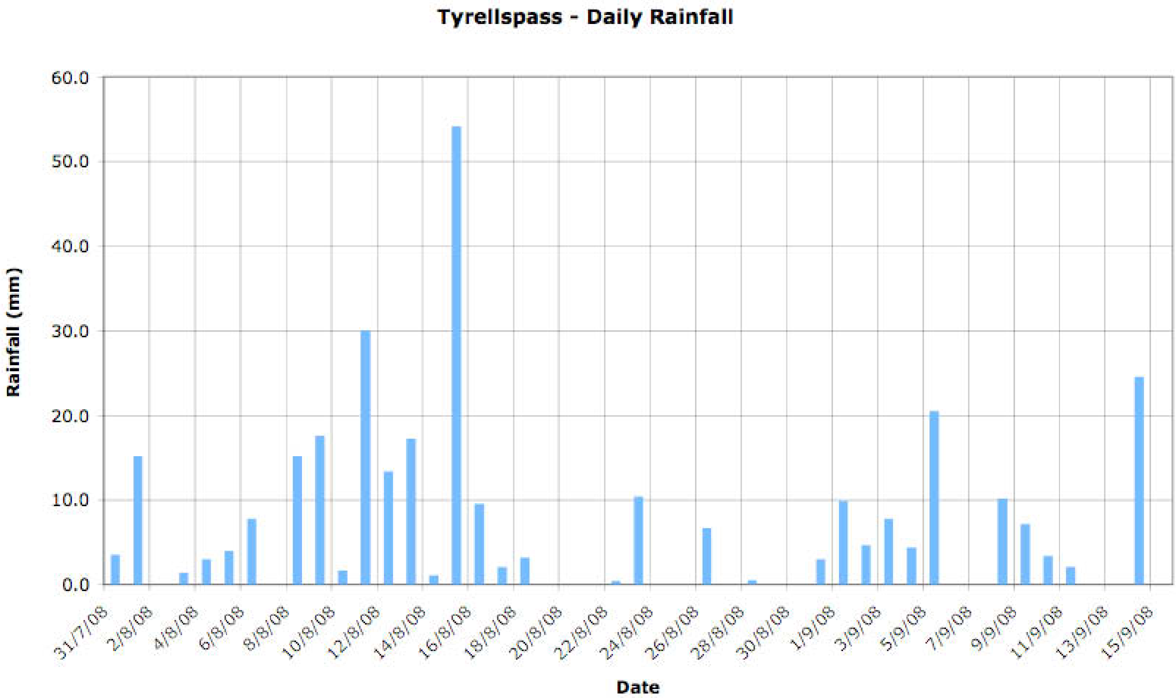
B.3d Ballinasloe



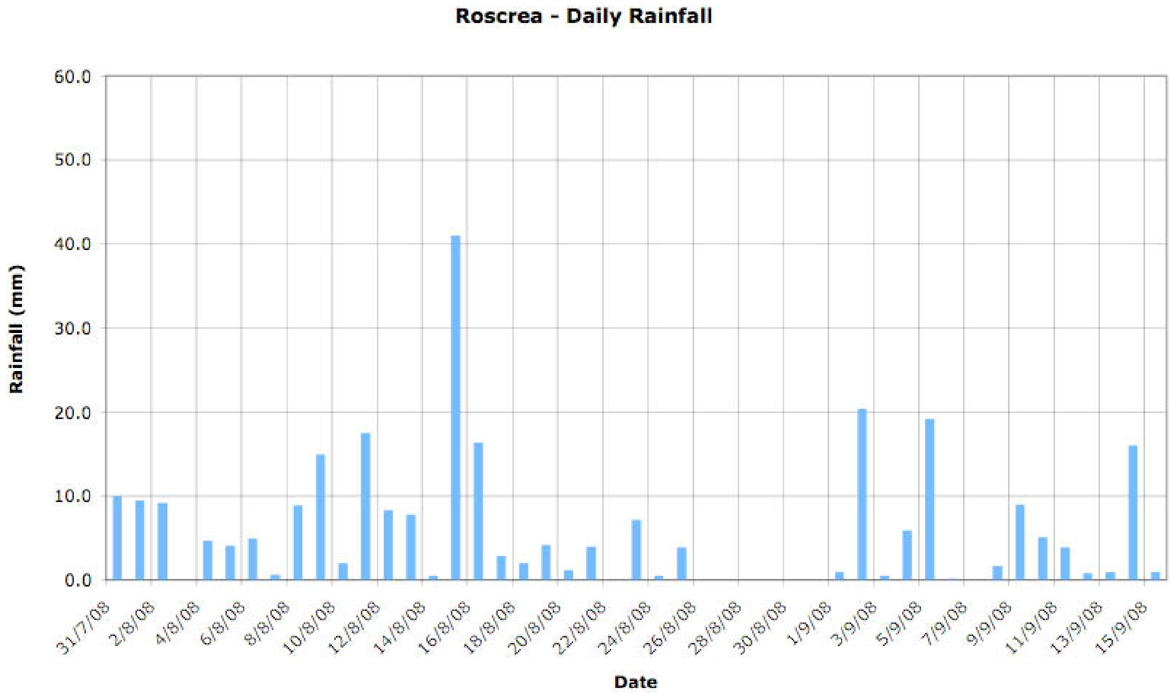
B.3e Bannagher



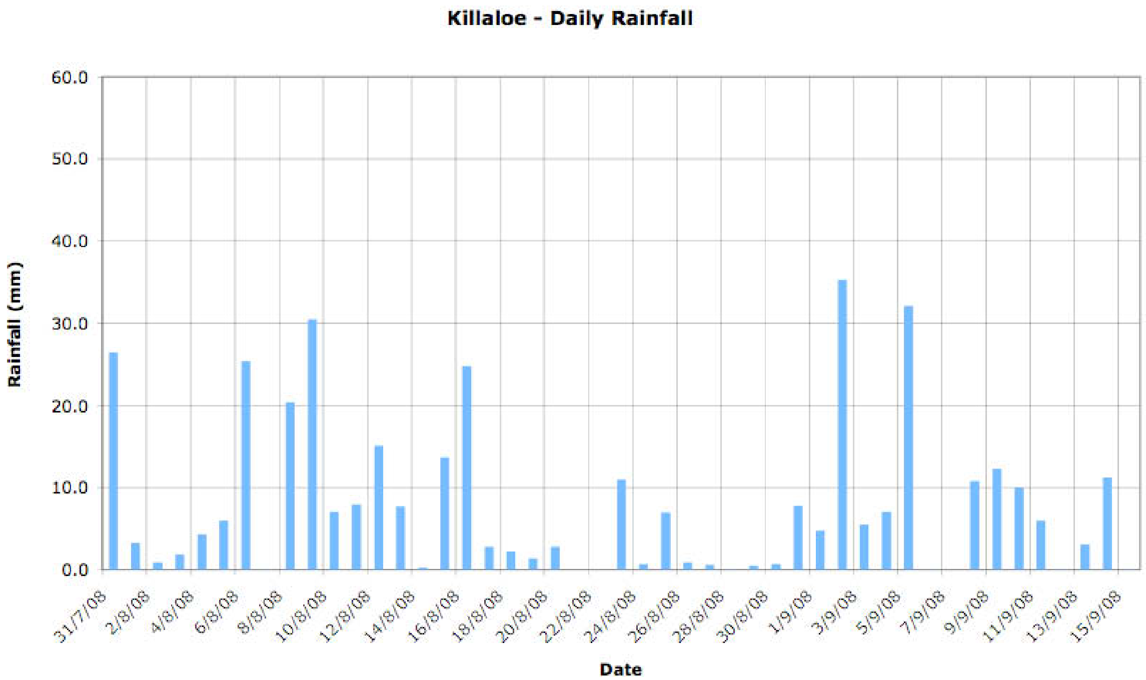
B.3f Tyrellspass



B.3g Roscrea



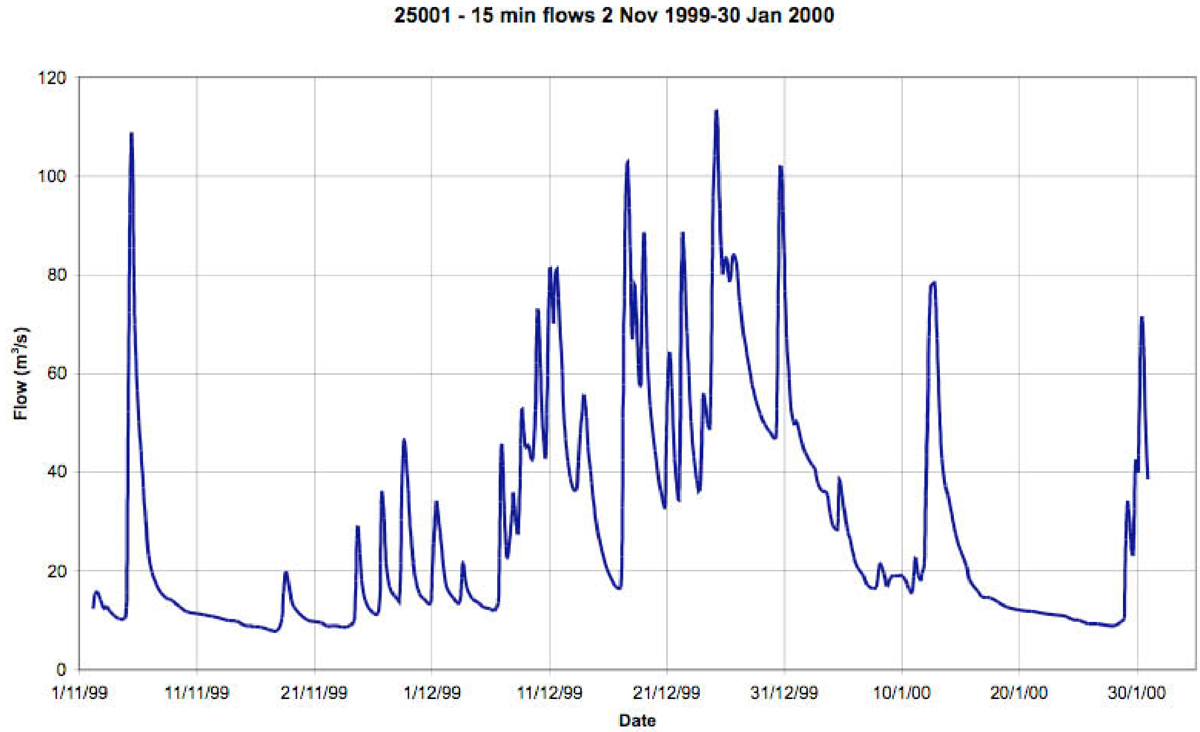
B.3h Killaloe



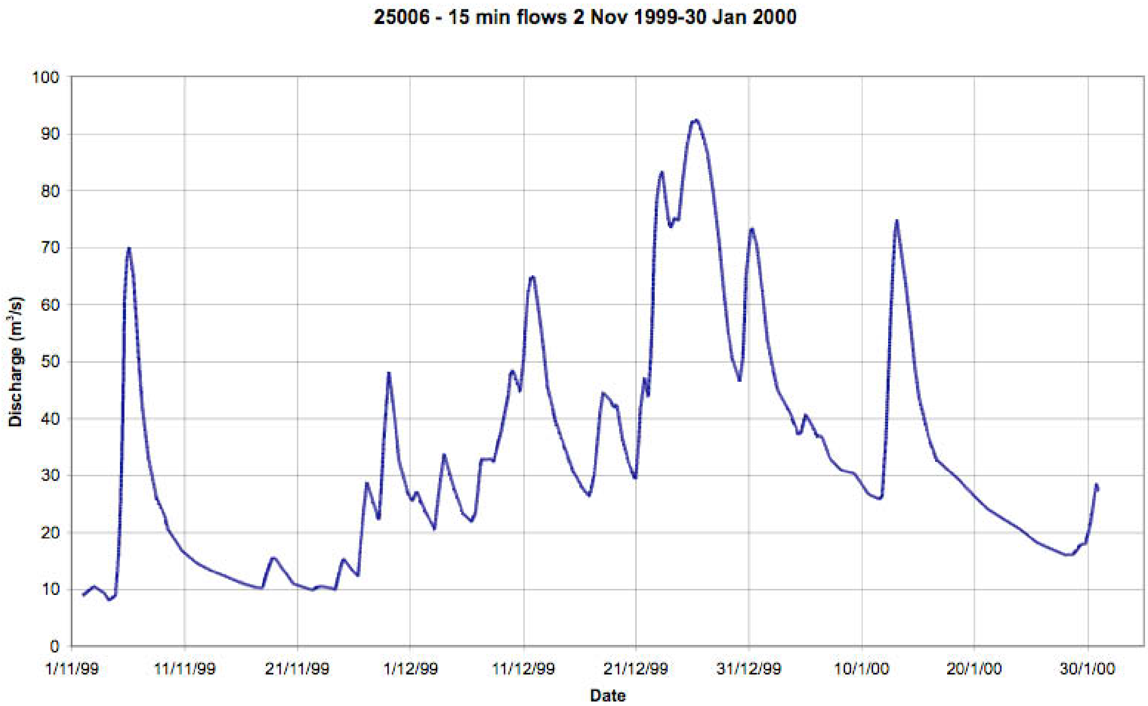
Appendix C Flood Event Data Graphs, November 1999 - January 2000

Figures C.1 (a – d) Typical Hydrographs

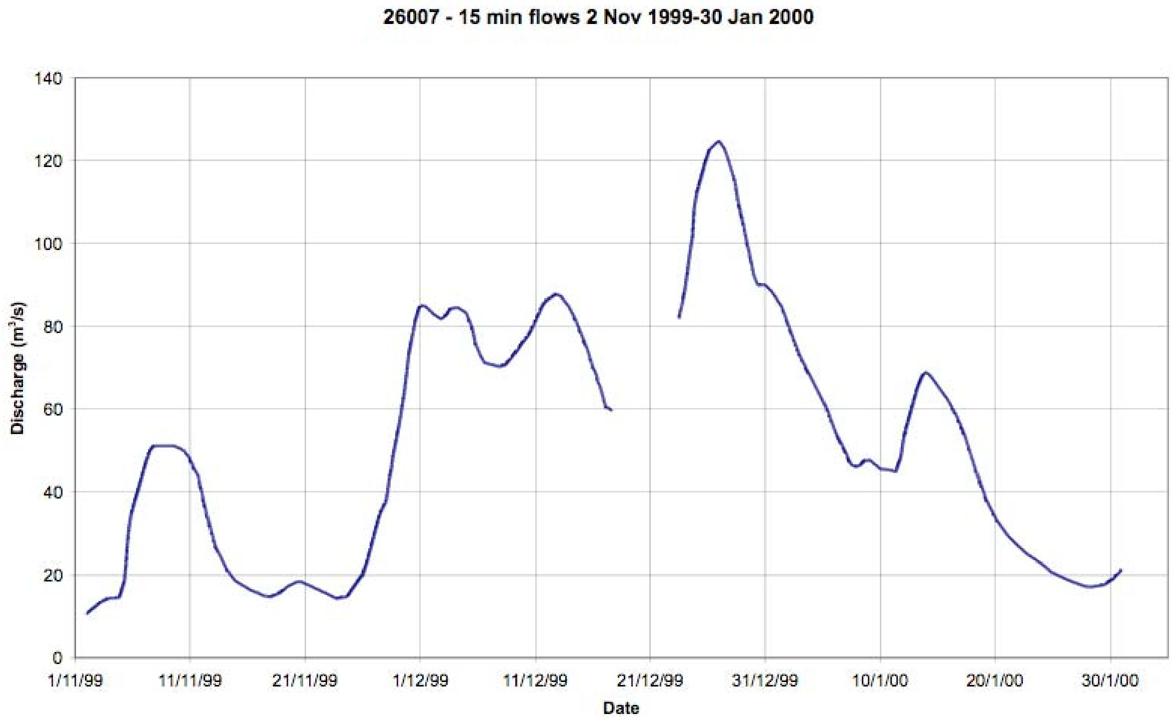
C.1a River Annacotty at Mulkear



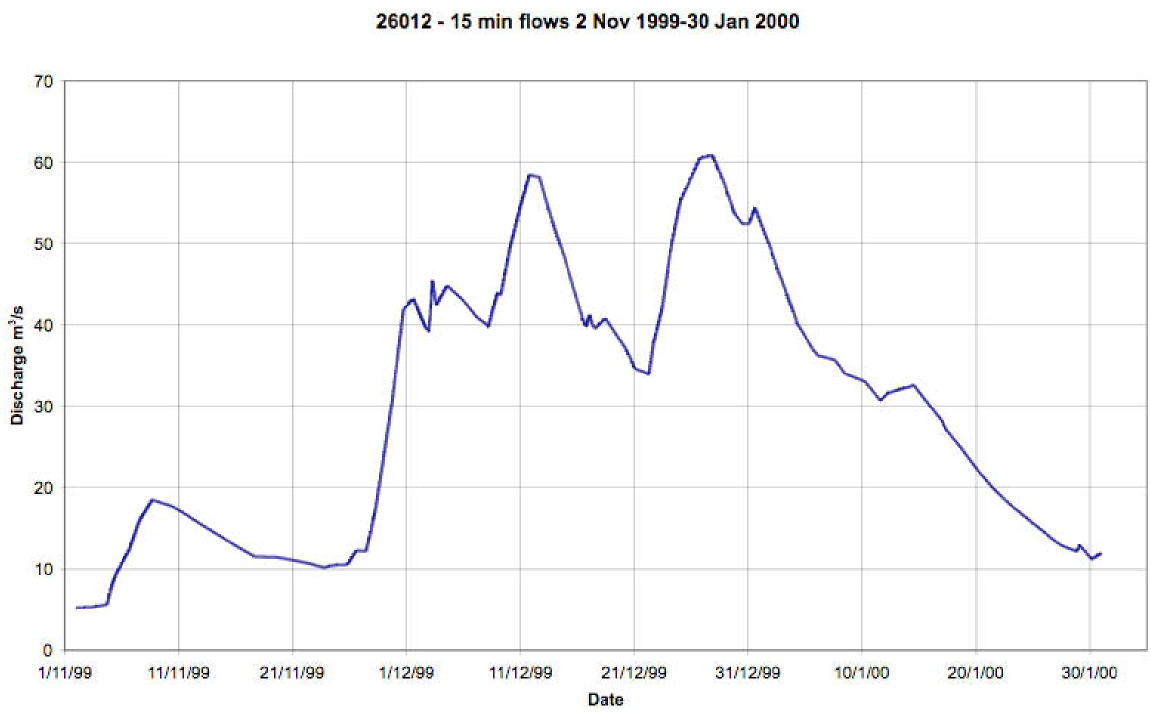
C.1b River Brosna at Ferbane



C.1c River Suck at Bellagill

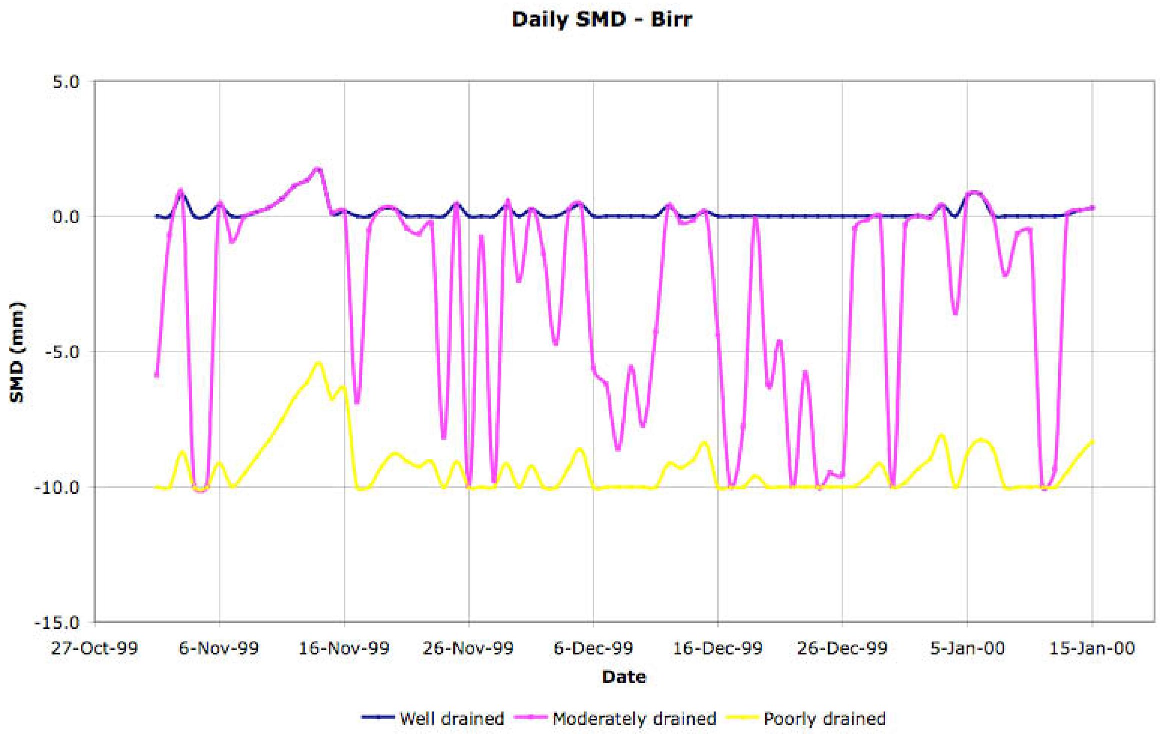


C.1d River Boyle at Tinacarra

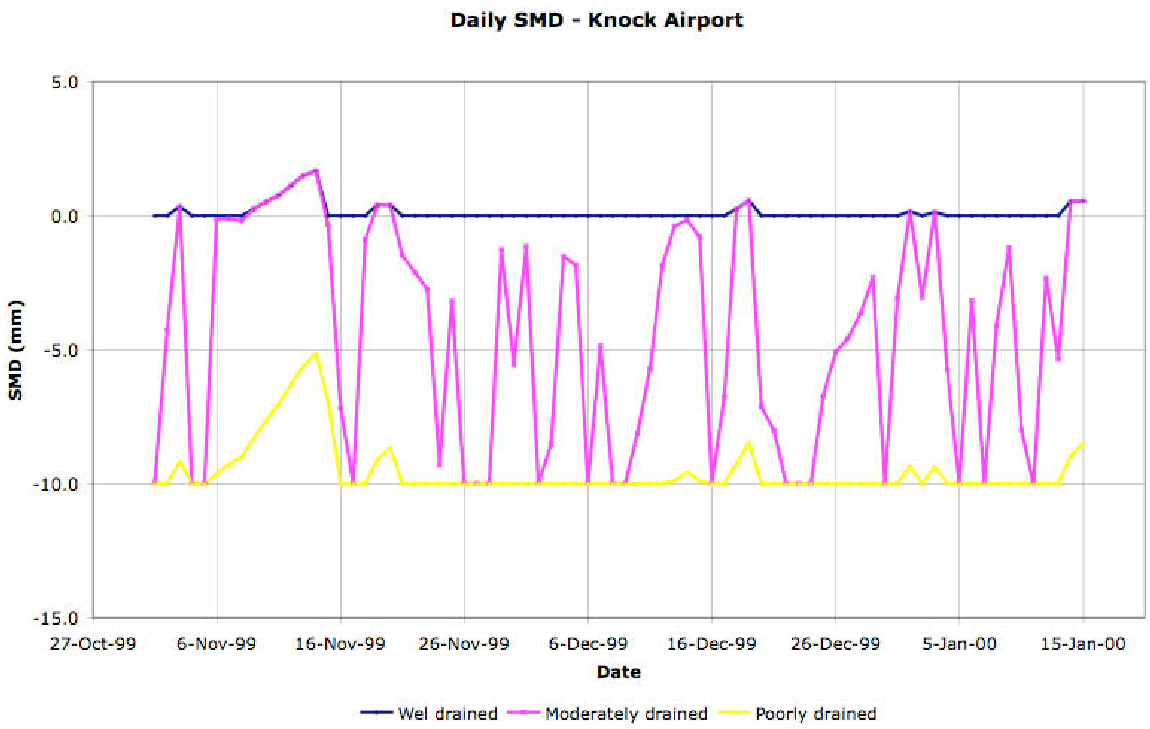


Figures C.2 (a – d) Soil Moisture Deficit Observations

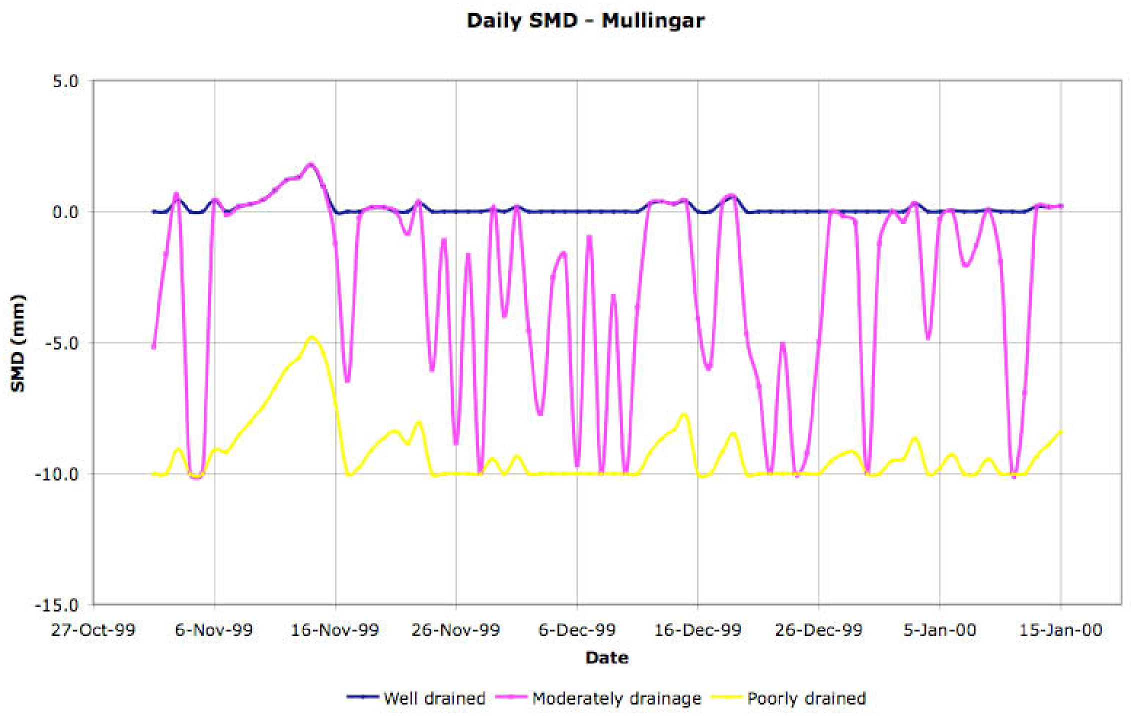
C.2a Birr



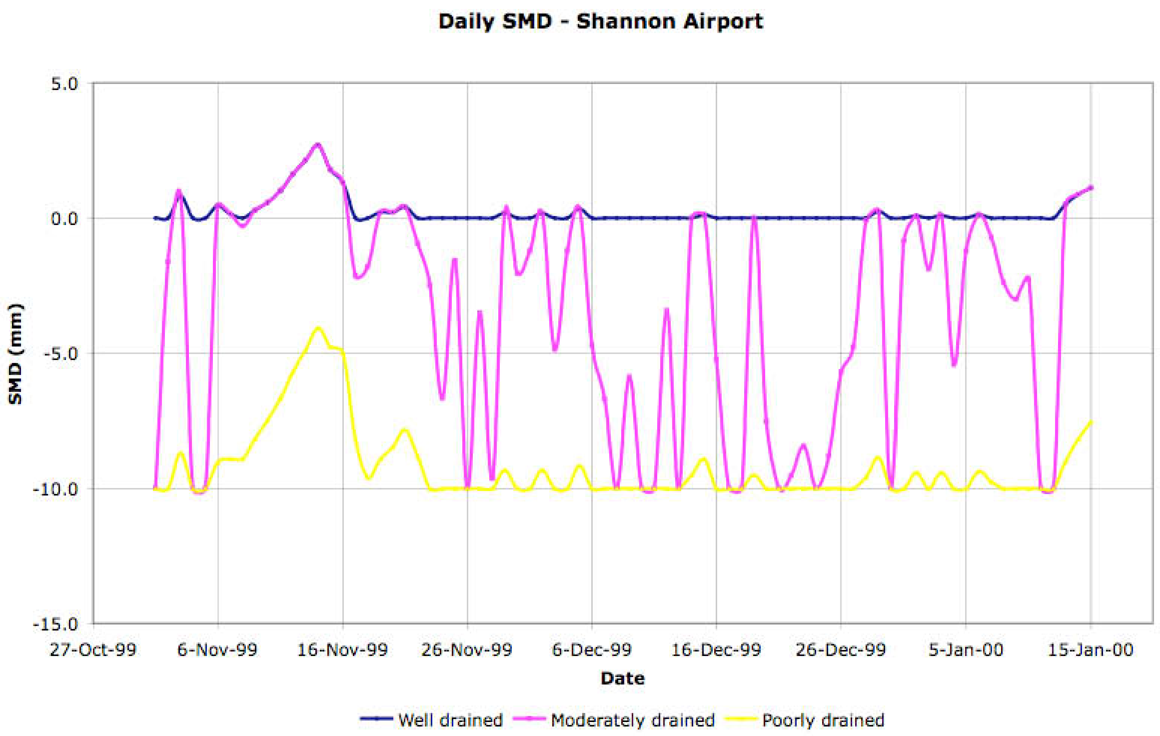
C.2b Knock Airport



C.2c Mullingar

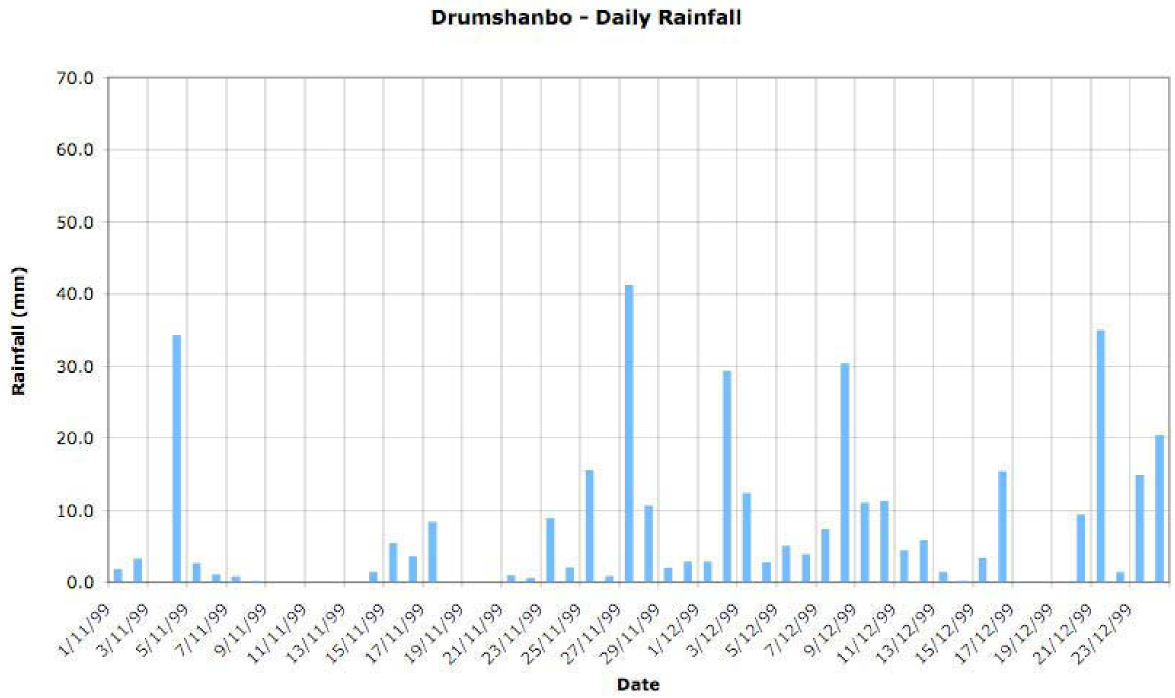


C.2d Shannon Airport

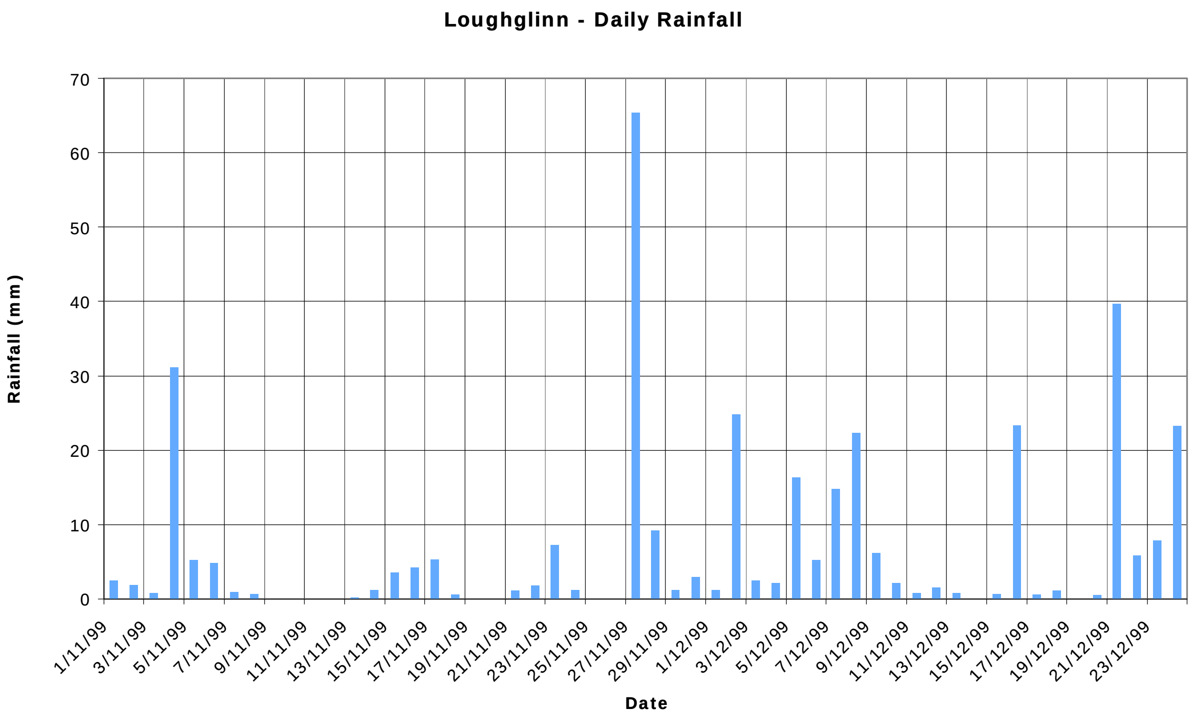


Figures C.3 (a – h) Sample hyetographs of daily rainfall

C.3a Drumshanbo



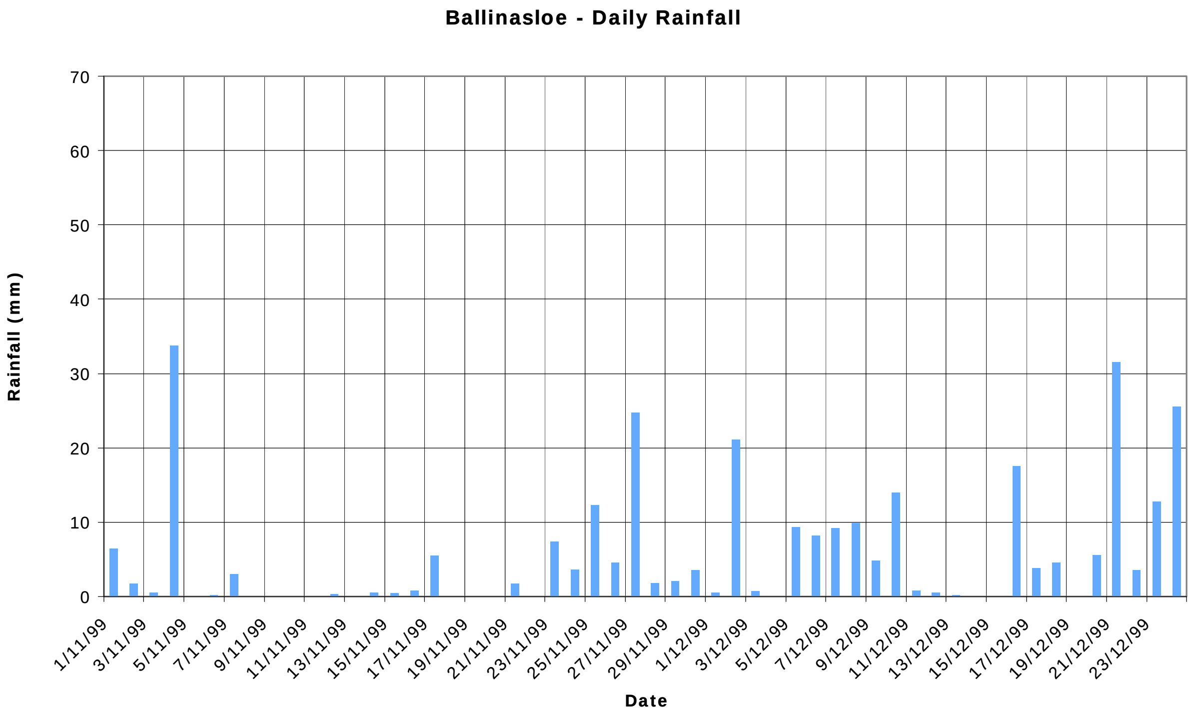
C.3b Loughglinn



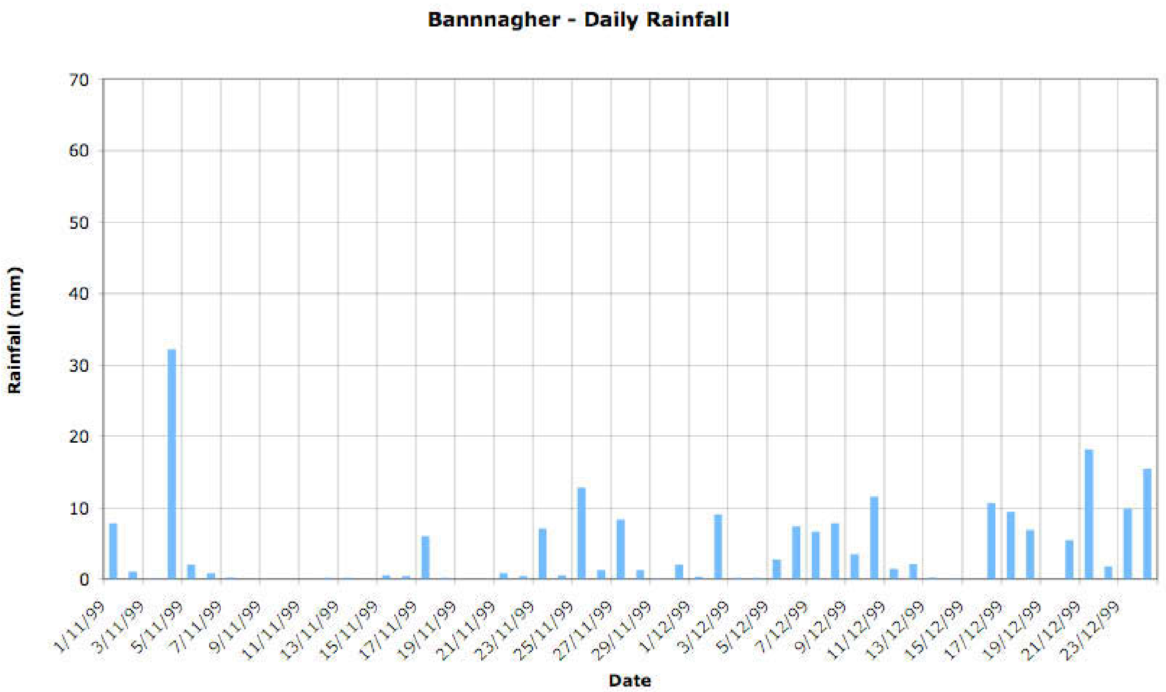
C.3c Coole

Data not available

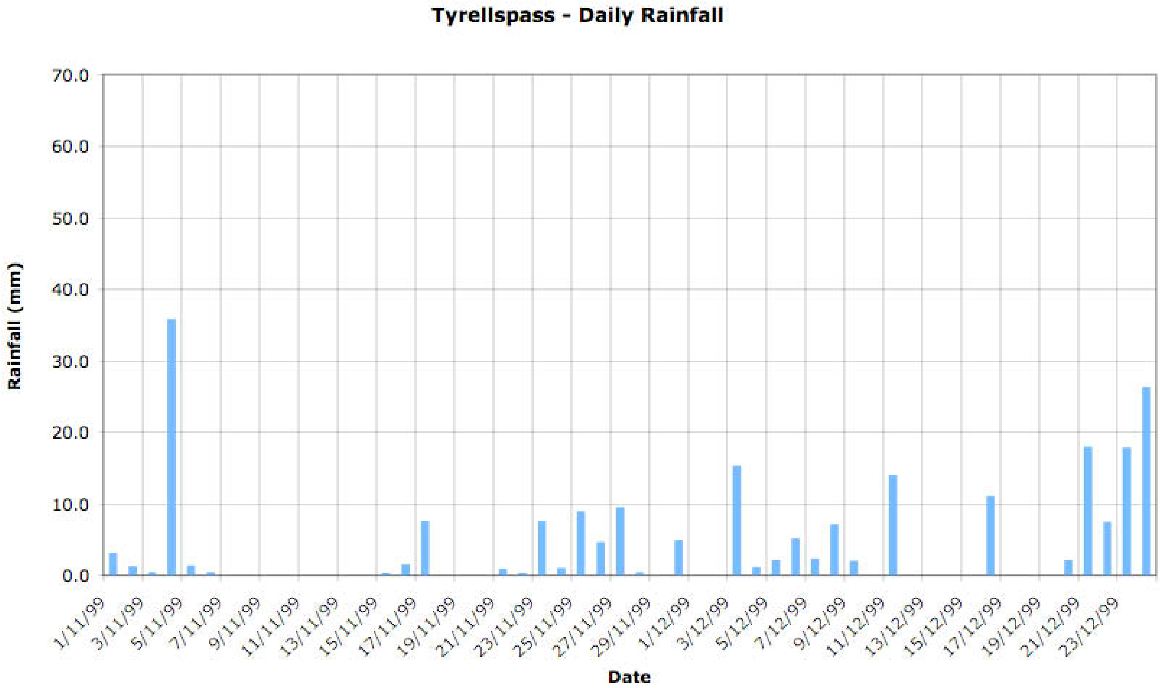
C.3d Ballinasloe



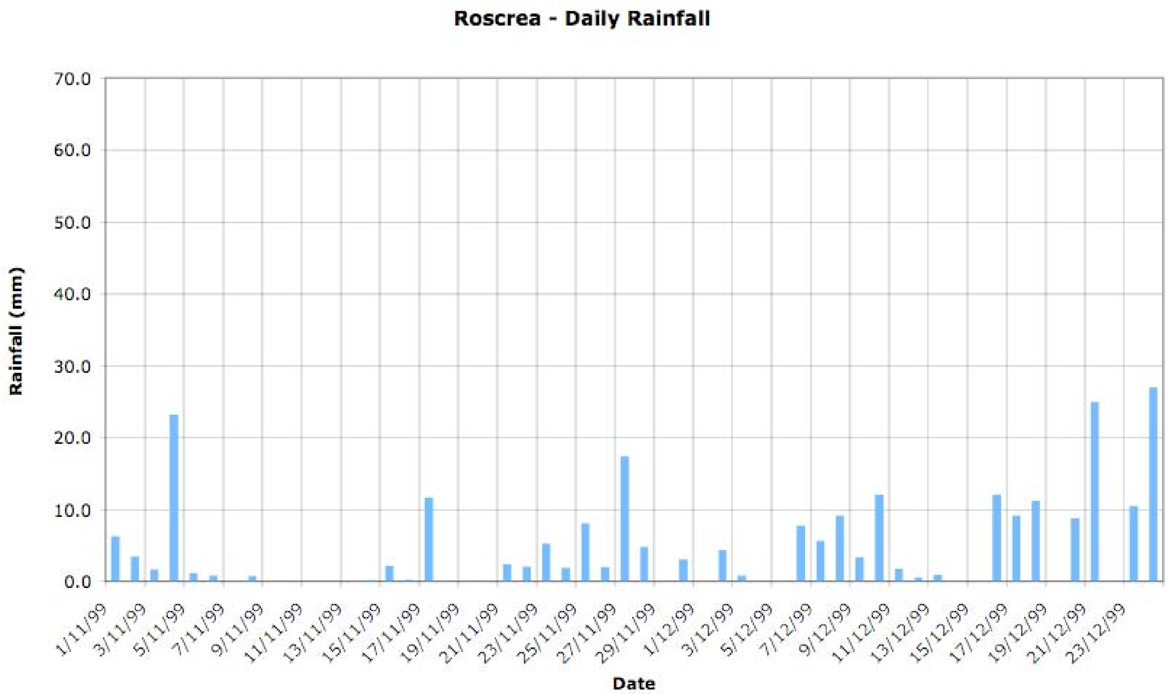
C.3e Bannagher



C.3f Tyrellspass



C.3g Roscrea



C.3h Killaloe