Flood Studies Update - WP 4.3

Assessing the Impact of Progressive Urbanisation at Catchment Scale

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EXECUTIVE SUMMARY

Urbanisation has been recognised in the past as contributing to significant increases in runoff in long term flood gauging records. This was considered in detail in the first edition of the flood studies report and our understanding of this phenomenon has been updated by various studies and reports since. More recently urbanisation has been proven to be a contributory factor to several severe floods in England, Wales and Ireland.

In the Dodder Catchment Flood Risk Assessment and Management Study (CFRAMS) the effect of increased urbanisation was considered in both the analysis of historic data, and the derivation of future scenarios. A significant part of this work was based on a combination of numerical modelling and historic data analysis, however a systematic analysis of the available gauging data in this context was outside the original scope of the study. Following on from the Dodder CFRAMS it was suggested that a methodical analysis of long term flow gauging data through a combination of historic data analysis and numerical modelling should be undertaken using the same hydrological models as employed in the Dodder CFRAMS.

Consequently this study explores the impact of urbanisation on extreme runoff based on the analysis of data from selected Irish catchments. Following a detailed review of available catchment data in Ireland, three catchments were identified, which showed a significant increase in urbanisation over the past 40 years and for which sufficiently long and reliable flow gauging records were available. These were the river Owendoher with the gauging station at Willbrook Road (Gauge No. 09009), the river Griffeen with the gauging station at Lucan (Gauge No. 09002) and the river Broadmeadow with the gauging station at Broadmeadow (Gauge No. 08008). All catchments are located in the Greater Dublin Area, principally as a consequence of the limited availability of good quality rainfall data with high temporal resolution for other areas of the Country.

Based on spatial data sets covering the period 1973 to 2008, the changes in urbanised extent within each of the catchments have been defined. Various statistical analysis tools were employed to assess the changes in recorded discharge for the three pilot catchments. This process was primarily based on peak over threshold or partial duration series analysis and an assessment of the number of events exceeding the threshold for progressive levels of urbanisation. The flood frequency analysis included visual trend analysis using different numbers of events per year, seasonality assessment, analysis of the data set through cumulative assessment and statistical trend analysis. The most recent discharge records were also used to calibrate a numerical hydrological model, comprised of an urban modelling module, based on deterministic runoff modelling from impermeable and semi permeable surfaces and a lump sum conceptual model simulating the runoff from the rural part of the catchment. Following development of models for all three catchments these were used to simulate runoff for four different epochs with different urban extents using the full available rainfall data set of 45 years. The resulting discharges were analysed using Annual Maxima Series and a full extreme value analysis was undertaken for the four epoch dataset, to determine discharge values for different return periods for each catchment and each degree of urbanisation. These were compared both in terms of absolute value and in relation to the Q_{med} value and the resulting growth factors.

Analysis of historic data sets indicated a significant change in runoff characteristics for the Griffeen catchment, which in the time span investigated has seen a dramatic increase in urbanisation, particularly in recent years. The absence of any significant changes in rainfall pattern in this catchment in the same time span indicates that urbanisation is the likely cause of this change in runoff. The analysis of the historical data from the Owendoher catchment does not conclusively indicate such a change in runoff. This is to a large extent due to the limited data available for the period, where the change in urbanisation was most dramatic, i.e. pre 1985. The analysis of the numerical modelling output for this catchment was more conclusive with some very clear trends in discharge being observed. The model also indicated significant differences between the growth factors as recommended by the FSR and those derived from the data. The simulations clearly showed the impact of decreasing permeability of the catchment surface on lower return period events, whereas extreme return period events of 1 in 50 year return period or higher are less effected. It also showed that the Q_{med}, often the basis for the derivation of design events, increased significantly with increasing

urbanisation. The study concluded that when assessing catchment runoff characteristics, the analysis of historic data combined with an assessment of changes in urbanisation over recent years is to be highly recommended. From this information extreme runoff values can be adjusted to more accurately represent present day and future scenarios.

1 HYDROMETRIC CATCHMENTS

A large number of hydrometric gauge catchments were examined for possible use in this study. The main criteria for choosing suitable catchments were as follows:

- The catchment must have undergone significant changes in urbanisation during the period of hydrometric record (increase in urbanisation of at least 5% of catchment area)
- Continuous long duration good quality hydrometric records should be available for the catchment, ideally with sub-hourly data intervals.
- Continuous 15 minute rainfall records of a duration corresponding to the hydrometric records should be available for a location within or in close proximity to the catchment.

Table 1.1 presents details of the catchments screened for use in this study.

Gauge Number	Gauge Name	River	Agency	Significant Change in Urbanisation	Hydrometric Data Available	Rainfall Data Available
07004	Stramatt	Blackwater (Kells)	OPW	No	-	-
07005	Trim	Boyne	OPW	No	-	-
07007	Boyne Aqueduct	Boyne	OPW	No	-	-
07009	Navan Weir	Boyne	OPW	No	-	-
07010	Liscarten	Blackwater (Kells)	OPW	No	-	-
07012	Slane Castle	Boyne	OPW	No	-	-
07037	Blackcastle	Boyne	OPW	No	-	-
07039	Johnstown Bridge	Blackwater (Enfield)	EPA	No	-	-
07041	Ballinter Bridge	Boyne	EPA	No	-	-
07059	Roughgrange	Boyne	EPA	No	-	-
07109	Kishawanny Weir	Boyne	EPA	No	-	-
08007	Ashbourne	Broadmeadow	EPA	Yes	Unreliable	-
08008	Broadmeadow	Broadmeadow	OPW	Yes	Yes	Yes
08009	Balheary	Ward	EPA	No	-	-
08011	Duleek D/S	Nanny	OPW	No	-	-
08017	Duleek U/S	Nanny	OPW	No	-	-
08018	Beaumont Bridge	Nanny	OPW	No	-	-
08020	Abbeyland (Duleek)	Nanny	OPW	No	-	-

Gauge Number	Gauge Name	River	Agency	Significant Change in Urbanisation	Hydrometric Data Available	Rainfall Data Available
09001	Leixlip	Ryewater	OPW	No	-	-
09002	Lucan	Griffeen	EPA	Yes	Yes	Yes
09009	Willbrook Road	Owendoher	EPA	Yes	Yes	Yes
14001	Carlow	Barrow	OPW	No	-	-
14003	Borness	Barrow	OPW	No	-	-
14005	Portarlington	Barrow	OPW	No	-	-
14006	Pass Bridge	Barrow	OPW	No	-	-
14018	Royal Oak	Barrow	OPW	No	-	-
14019	Levitstown	Barrow	OPW	No	-	-
14022	Barrow New Bridge	Barrow	OPW	No	-	-
14029	Graiguenamanagh U/S	Barrow	OPW	No	-	-
25012	Groody Bridge	Groody	OPW	Yes	No	-
27002	Ballycorey	Fergus	OPW	No	-	-
27003	Corrofin	Fergus	OPW	No	-	-

Table 1.1 Hydrometric Catchments Screened for Use in Study

Thus only three hydrometric catchments were identified that broadly met the criteria for inclusion in this study as follows:

- Broadmeadow at Swords (OPW Gauge No. 08008)
- Griffeen at Lucan (EPA Gauge No. 09002)
- Owendoher at Willbrook Road (EPA Gauge No. 09009)

1.1 DATA COLLECTION & ANALYSIS

1.1.1 Owendoher at Willbrook Road (Gauge No. 09009)

The hydrometric gauge at Willbrook Road was analysed in detail as part of the River Dodder Catchment Flood Risk Assessment and Management Study (CFRAMS). All data used in relation to this gauge was sourced for the Dodder CFRAMS.

1.1.1.1 Catchment Description

The Owendoher rises at Kilakee in the Dublin Mountains, at an elevation of approximately 570mOD. It flows in a northerly direction through Edmondstown and Ballyboden before joining the River Dodder Main Channel at Bushy Park in Rathfarnham. The stream is approximately 9.9km in length, falls at an average gradient of 1 in 19 and drains a catchment of approximately 23.5km^2 including the Whitechurch catchment.

The Whitechurch is a tributary of the Owendoher and rises between Tibradden and Kilmashogue Mountains at an elevation of approximately 480mOD. It flows in a northerly direction through Marley Park and St. Enda's Park and onto Willbrook where it meets the Owendoher. The stream is approximately 7.7km in length, falls at an average gradient of 1 in 18 and drains a catchment of approximately 8.9km^2.

The water level gauging station at Willbrook Road is located on the Owendoher stream approximately 150m downstream of its confluence with the Whitechurch stream and immediately upstream of the footbridge to Glenbrook Park off Willbrook Road. The catchment upstream of the gauge is approximately 22.6km^2.

The urban areas within this gauge catchment include the Dublin suburbs of Ballyboden, Edmonstown and Willbrook. Currently these areas account for approximately 15% of the hydrometric gauge catchment.

Figure 1-1 shows the location of the Owendoher catchment upstream of the Willbrook Road gauge.

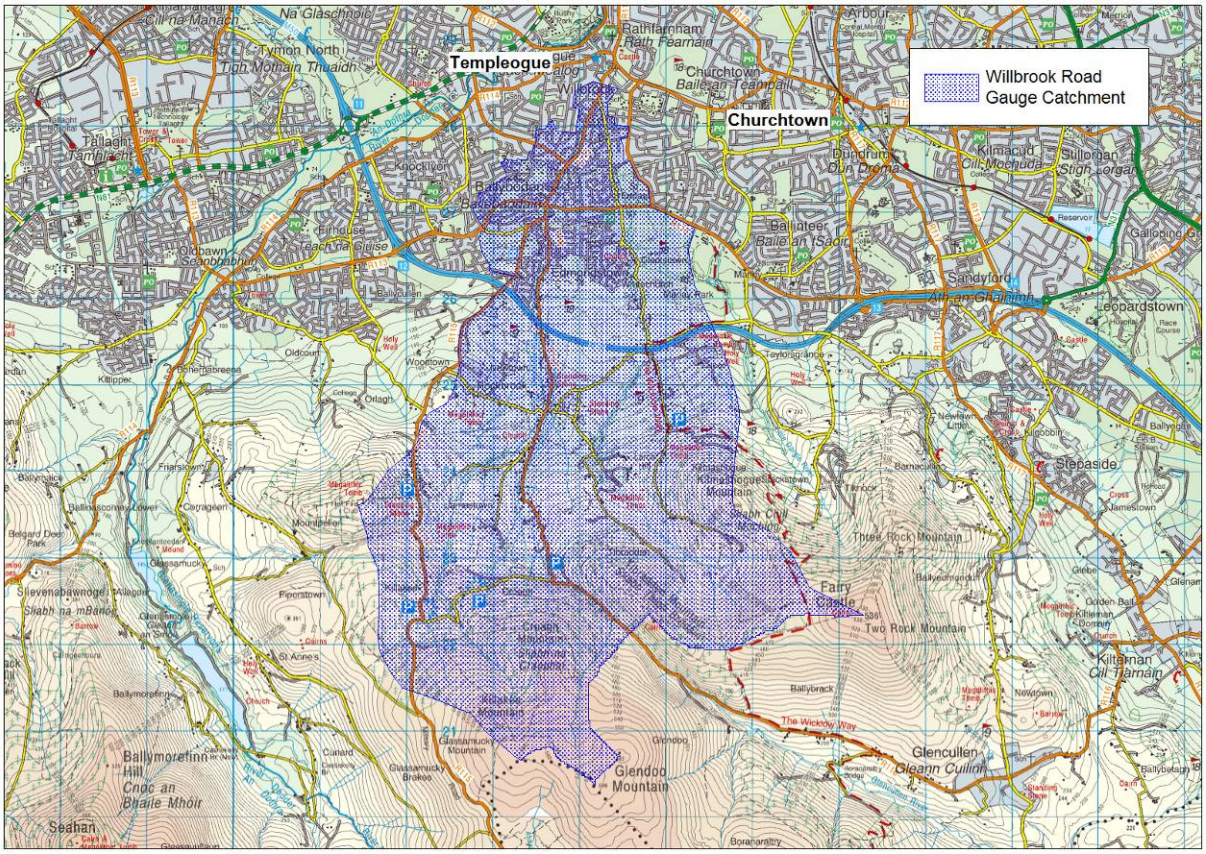


Figure 1-1 Willbrook Road Gauge Catchment (Owendoher)

1.1.1.2 Hydrometric Data

The Owendoher is approximately 5m wide at the site of the gauging station and is canalised with stone walls on both the left and right banks. South Dublin County Council installed a water level recorder at Willowbrook Road in 1980 and erected a channel control at the station in 1996. The recording equipment was further updated in 2002. The EPA provided 60 minute discharge data from 1980 to 2002 and 15 minute data from 2002 to 2007 from this gauging station for use in the Dodder CFRAMS.

1.1.1.3 Meteorological Data

The nearest Met Eireann synoptic station to the Willbrook Road gauge catchment is Casement Aerodrome, approximately 9km away. A number of daily rainfall recording stations are located within or adjacent to this hydrometric catchment as follows: Glenasmole (Castlekelly), Glenasmole (Supt.'s Lodge), Knocklyon (St. Colmcille's), Ballyboden, Rathfarnham (St. Columba's), Tibradden (Larch Hill) and Ballyedmonduff House.

A representative rainfall file was generated for this hydrometric gauge catchment by entering the daily rainfall data from all gauges into a MIKE NAM model and weighting them according to their contribution relative to the catchment area using Voronoi polygons. The rainfall was then temporally distributed according to the rainfall pattern from the hourly rainfall data recorded at Casement Aerodrome. The resulting rainfall file spans the years 1964 to 2007 (the available data record length of the combined rainfall stations used in the MIKE NAM model).

1.1.2 Griffeen at Lucan (Gauge No. 09002)

1.1.2.1 Catchment Description

The River Griffeen rises at Saggart Hill above the town of Rathcoole in South Co. Dublin. It flows in a north-easterly direction towards the River Liffey at Lucan village, passing west of Casement Baldonnel Aerodrome and underneath the Grand Canal near the 12th lock. It is approximately 11km in length and has a catchment area of approximately 38.8km^2. From Saggart Hill to Rathcoole the river falls approximately 110m over a distance of 3km, while it falls another 100m over the remaining 8km of its length. The water level gauge on the River Griffeen is located downstream of Lucan Road Bridge, approximately 250m from its confluence with the River Liffey with an upstream catchment of approximately 35km^2.

The urban areas within this gauge catchment include Rathcoole, Greenogue Business Park, Casement Baldonnel Aerodrome, parts of Clondalkin, Ronanstown and Lucan. Currently these areas account for approximately 25% of the hydrometric gauge catchment.

Figure 1-2 shows the extent of the Griffeen catchment upstream of the Lucan gauge.

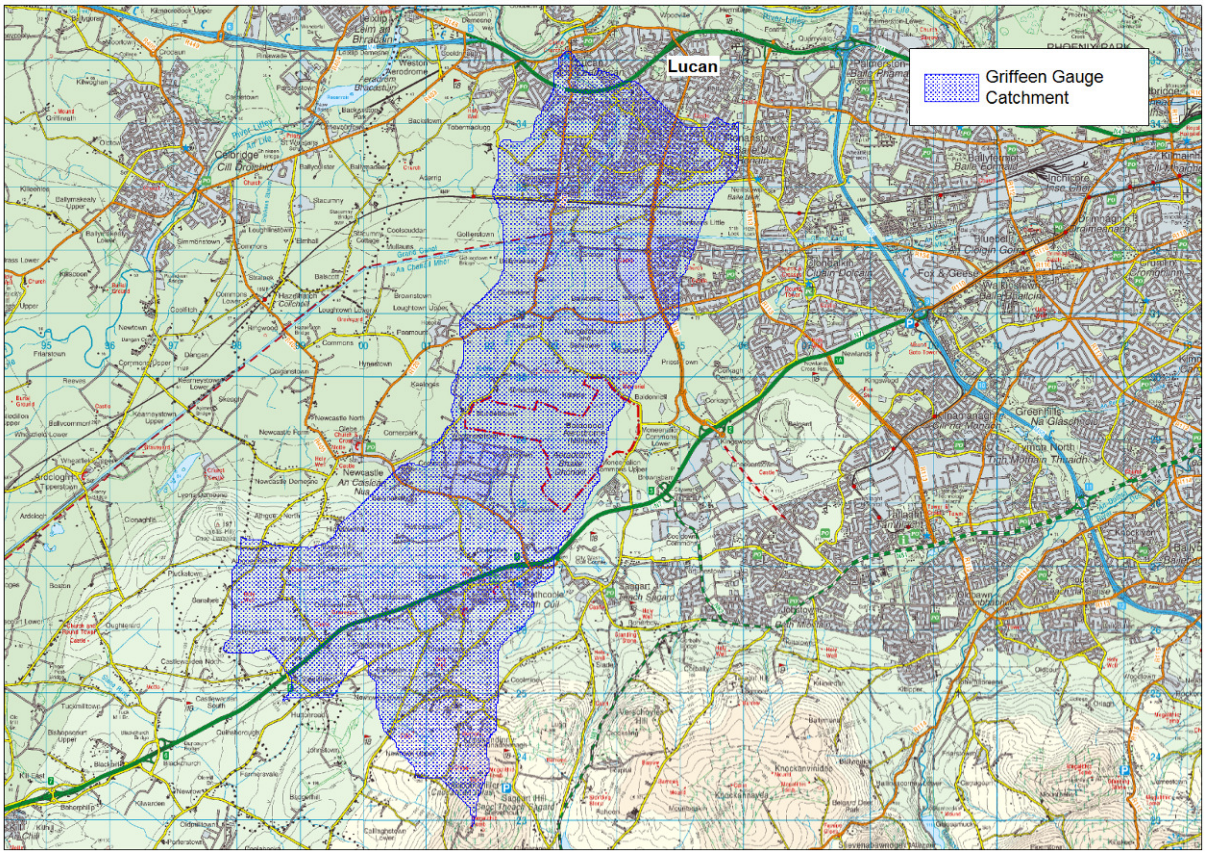


Figure 1-2 Lucan Gauge Catchment (Griffeen)

1.1.2.2 Hydrometric Data

The water level gauge on the Griffeen River at Lucan has been recording since March 1977. A chart recorder was used at this site between 1977 and 2002 and a digital data logger was installed in 2002. There is discharge data available between 1977 and 2002 but the site has not been rated since 2002 and therefore there is no discharge data available from this date. However, 15 minute water level data is available from this gauge from 2002 to 2008 although due to flood alleviation works undertaken on

the river in the vicinity of the hydrometric gauging station there is a gap in the available information between February 2003 and February 2004. All water level and discharge data for this gauge has been provided by the EPA.

In September 2001 Hydro Environmental Ltd. prepared a report for JB Barry & Partners on Hydraulic Modelling of the River Griffeen at Lucan Village. This report included details of a modelled rating curve prepared for the hydrometric gauge site at Lucan. From examination of this report and following discussions with the OPW it was agreed that Hydro Environmental's rating curve should be applied to the pre-2004 recorded water levels from this gauge site to produce appropriate discharge values. For this reason, Hydro Environmental's modelled rating curve has been digitised and applied to the pre-2004 recorded water depths and a time series of discharges produced for 1977 to 2004.

The weir and river channel at the hydrometric station was altered as part of the flood alleviation works undertaken on the River Griffeen in 2003-2004. As-built survey drawings for the weir and the river channel in this area were obtained from JB Barry & Partners Ltd. and a hydraulic model of the weir site was constructed using the MIKE suite of software. The river channel for a length of approximately 280m was defined using 11 cross-sections with information taken from the as-built data and the weir was modelled as a hydraulic structure. The model was calibrated using all available discharge and level data.

A revised rating curve was produced for this site using the calibrated hydraulic model. This rating curve was then applied to the post-2004 water level records to produce associated discharges. Further details of the hydraulic model and derived rating curve are presented in Appendix A.

A summary table of the hydrometric data for this gauge is presented in Table 1.2 below.

Data Period	Data Available from EPA	Rating Curve Used
Mar. 1977 to Mar. 2002	Water Levels & Discharge	Hydro Environmental
Mar. 2002 to Feb. 2003	Water Levels	Hydro Environmental
Feb. 2003 to Feb. 2004	No Data	-
Feb. 2004 to Dec. 2008	Water Levels	Post-2004 Hydraulic Model

Table 1.2 Summary Table of Hydrometric Data for Griffeen at Lucan Hydrometric Gauge

Both the Hydro Environmental and Post-2004 Hydraulic Model rating curves are presented in Figure 1-3 for comparison purposes along with pre and post 2004 measured data points.

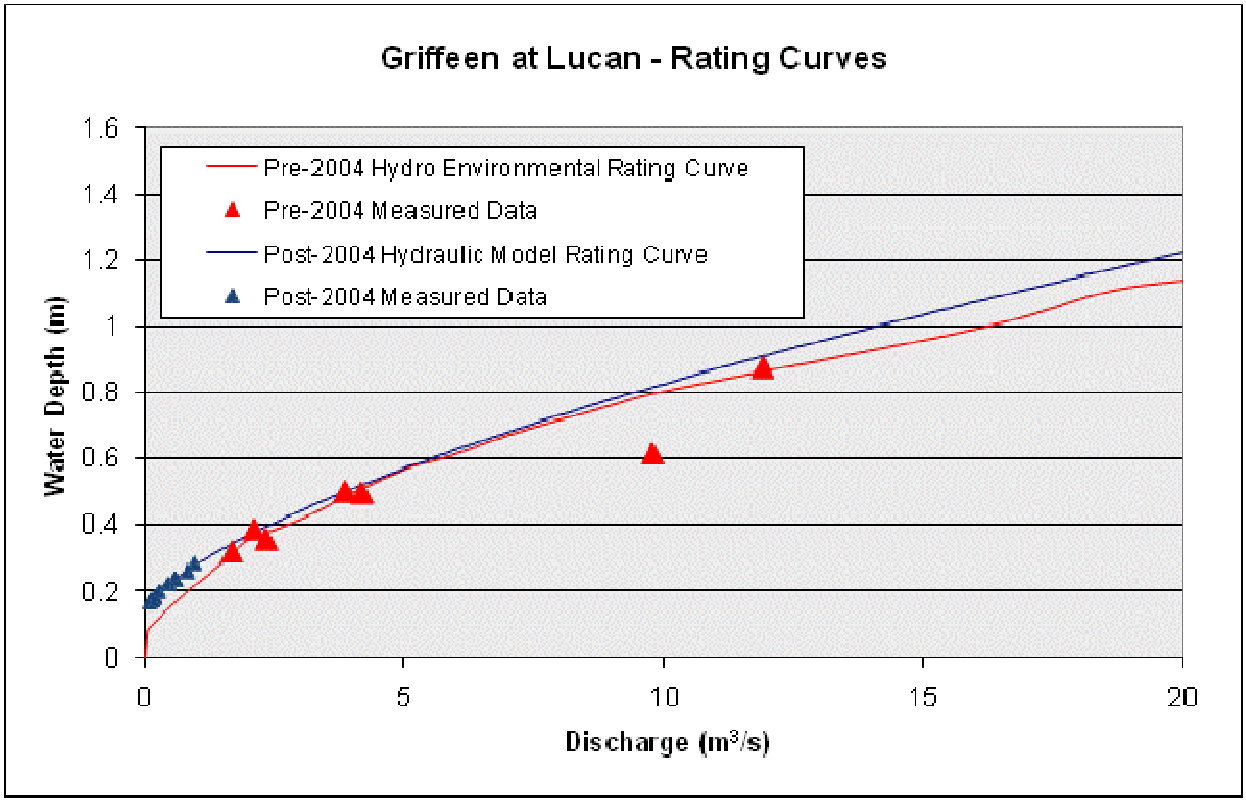


Figure 1-3 Griffeen at Lucan – Rating Curves for Hydrometric Gauge

1.1.2.3 Meteorological Data

A Met Eireann synoptic station is located at Casement Baldonnel Aerodrome which lies at the boundary of the Lucan hydrometric gauge catchment of the River Griffeen. Hourly rainfall depths are available from this synoptic station from 1969 to 2008. Rainfall data is also available for three other Met Eireann stations in close proximity to the catchment; Rathcoole – Saggart, Leixlip and Brittas (Glenarneen). However, these stations only record rainfall on a daily basis.

Given the location of the synoptic station within the Lucan hydrometric gauge catchment and the long duration, temporally detailed, rainfall data available, information from this station was used in this study.

1.1.3 Broadmeadow at Swords (Gauge No. 08008)

1.1.3.1 Catchment Description

The River Broadmeadow rises in high ground north of Dunshaughlin, Co. Meath. It flows in an easterly direction through the towns of Ratoath and Ashbourne before entering the Malahide Estuary north of Swords in Co. Dublin. It is approximately 29km in length and has a catchment area of approximately 115km^2. The river falls at an average gradient of 1 in 250 over its entire length. The water level gauge on the River Broadmeadow is located approximately 850m upstream of Balheary Road Bridge in Swords, approximately 2km from the Broadmeadow Rivers' outlet. The catchment upstream of the gauge is approximately 108km^2.

The urban areas within this gauge catchment include the towns of Ratoath, Ashbourne and parts of Dunshaughlin and Swords. Currently these areas account for approximately 6% of the total area of the hydrometric gauge catchment. Figure 1-4 shows the extent of the Broadmeadow catchment upstream of the Swords gauge.

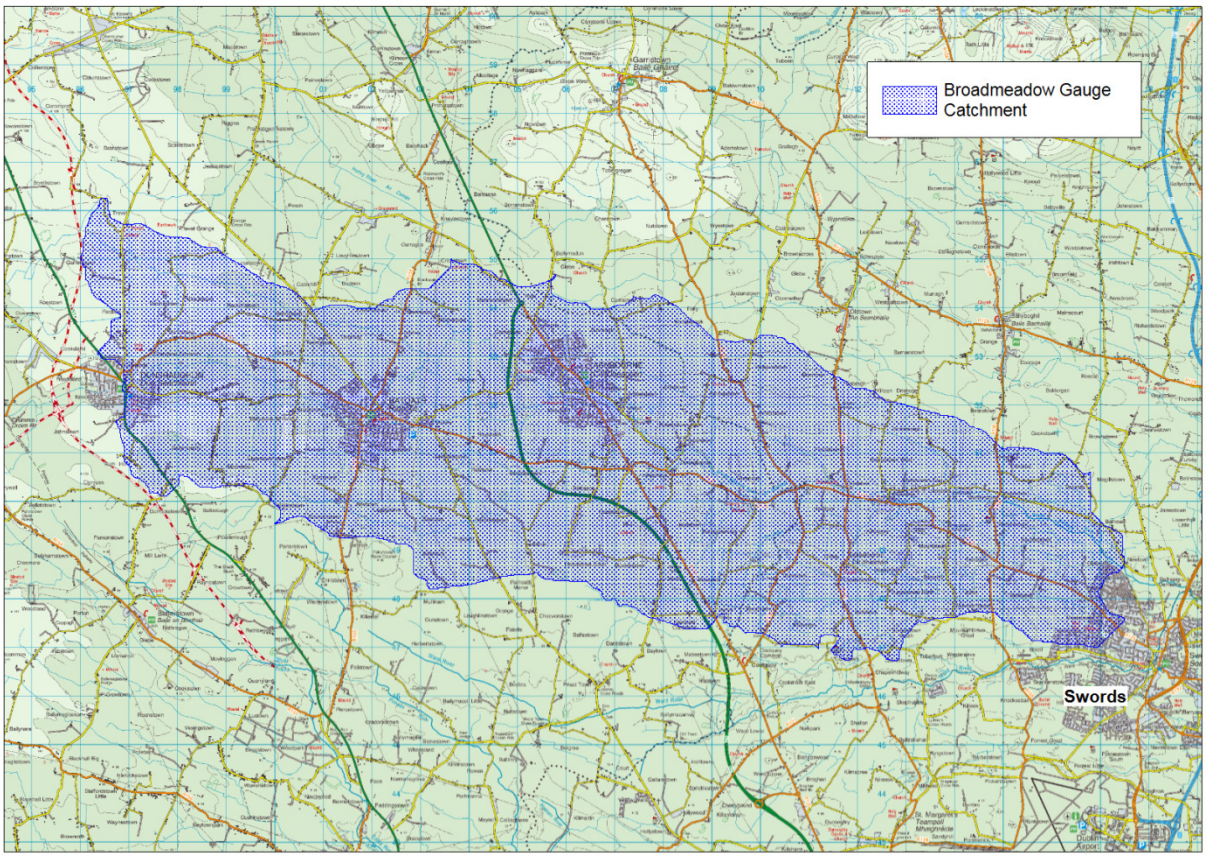


Figure 1-4 Swords Gauge Catchment (Broadmeadow River)

1.1.3.2 Hydrometric Data

The hydrometric gauge is located on the Broadmeadow River at Swords in north County Dublin and encompasses Ratoath, Ashbourne and parts of Dunshaughlin and Swords in its catchment area. A chart recorder has been located at this site since 1977 and the OPW have provided discharge data from this gauge covering the period 1977 to 2008. A full rating curve is not available for this site at present as more discharge observations are required at low flows. However, some measured water levels and corresponding discharges along with rating equations were made available for use in this study by the OPW.

A rating curve was generated for this gauge site using the data supplied by the OPW. This rating curve was applied to the recorded water levels from 1977 to 2008 and corresponding discharges were generated for these years.

1.1.3.3 Meteorological Data

There is a Met Eireann synoptic station located at Dublin Airport, approximately 4km south of the Broadmeadow hydrometric gauge catchment. Hourly rainfall depths are available for the synoptic station from 1960 to the present day and were used in this study.

2 ANALYSIS OF CHANGES IN URBANISATION USING SPATIAL DATA

Recent changes to the urban fraction of the three hydrometric gauge catchments selected for this study were investigated. The purpose of this task was to identify and quantify any significant changes in catchment urbanisation over distinct time intervals to facilitate comparison with flow records at the gauging sites.

2.1 METHOD OF ANALYSIS

The boundaries of the three gauge catchments were delineated using ArcGIS software as shown in Figure 2-1 below.

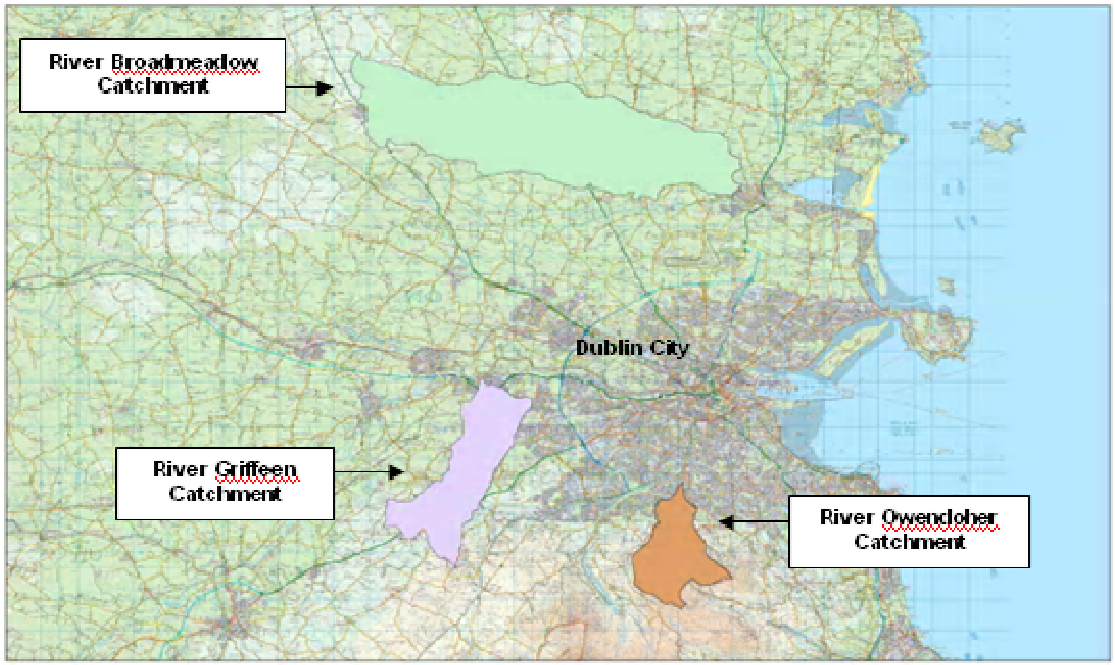


Figure 2-1 Catchment Boundaries

An initial assessment of the extent of urbanised development within these three catchment boundaries was carried out using satellite imagery. This data was sourced from the United States Geological Society (USGS) which provides a web-based interface storing global satellite data from 1972 to the present day (Earth Explorer). LandSat thematic and multi-spectral maps for specific time periods were examined for the relevant areas however the images were not clear as most had significant cloud cover over the areas of interest. Figure 2-2 below shows an example satellite image with cloud cover over Ireland.

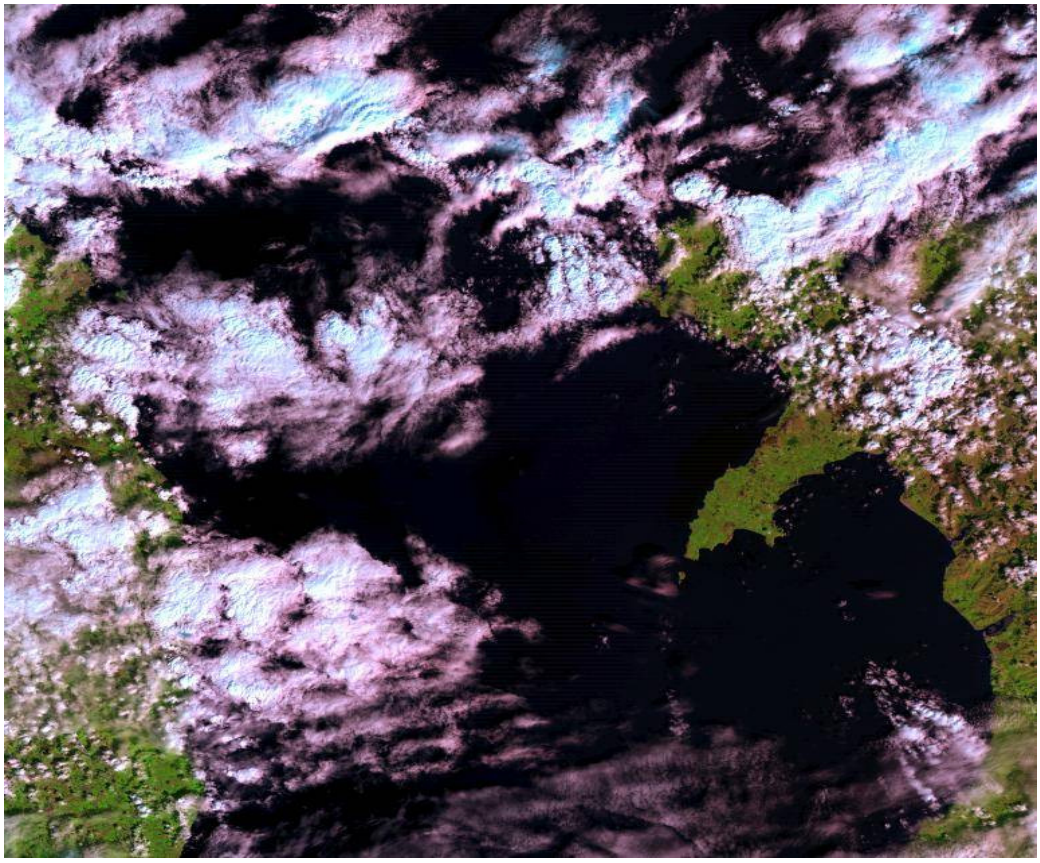


Figure 2-2 LandSat Image from USGS

Due to the limited suitability of the satellite imagery, the potential use of aerial photography for the relevant areas was investigated. Example aerial photography of the Willbrook Road gauge catchment on the Owendoher is shown in Figure 2-3.

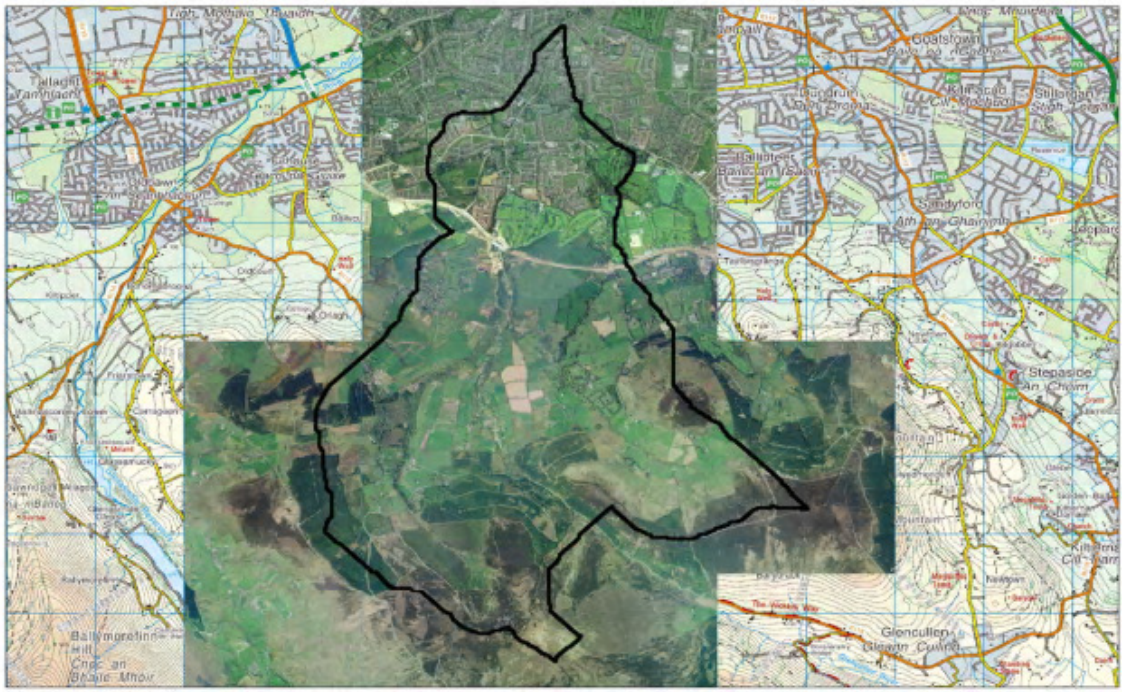


Figure 2-3 Aerial Photography of Willbrook Road Gauge Catchment for 2000

It can be seen from the above diagram that even at the plotted scale the different land uses can easily be identified in the digital colour aerial photography from 2000. The earlier photographic series (1973 & 1995) are grey scale photography digitised from the original negative obtained during the fly-over. The 2000 aerial photography as provided to the project team had a pixel resolution of several metres, allowing identification of roads and individual houses. Consideration was given to a range of potential methods for identifying urbanised areas. Following some trials it was decided that identifying urbanised areas through manual assessment of the existence of houses and other surfaced areas likely to be drained to storm water networks or directly into the river network was most reliable. Other computerised methods required a scaling of the more recent photography to the same quality as the 1973 aerial photography to obtain consistent results, which would require extensive calibration. Thus manual contouring was preferred, even though this involved some degree of subjectivity on behalf of the person digitising the information. However this was minimised by ensuring that the same person undertook the analysis for each area.

Other spatial data sources investigated for use in this study included the following:

- **Vector Mapping**

  The Ordnance Survey Ireland (OSI) vector mapping is not provided for specific dates. It is updated on an ongoing basis and it is therefore not possible to assign a date to a particular area of interest. Due to the importance of documenting the changing urban development for distinct time intervals, the vector mapping was not deemed appropriate for use in this analysis.

- **Corine Land Cover Maps**

  These maps did not provide any more detail on urbanised areas than the aerial photography data and therefore offered no additional benefit to the analysis.

- **Development Plan Maps**

  These maps show desired or intended development within the relevant catchments but do not show actual development. In some cases older development plans can be shown to differ greatly from actual urban development that follows. For this reason they were not investigated in detail for this study.

2.2 VARIATION OF URBAN EXTENT DERIVED FROM SPATIAL DATA

Aerial photography was provided by the OPW for the years 1973, 1995 and 2000 while the most up-to-date aerial photography (2008) was examined using internet images (Google Maps). All areas that were considered urban, including residential, commercial, civic, airfields and sport and leisure facilities were identified on the aerial photographs and their extents delineated. Table 2.1 and Table 2.2 present the change in urban area in each of the three gauge catchments and Figure 2-4 to Figure 2-6 present the same data in pictorial format.

Year / Growth in km^2 and % increase to previous period	Gauge Catchments		
	Owendoher at Willbrook Road (Gauge No. 09009)	Griffeen at Lucan (Gauge No. 09002)	Broadmeadow at Swords (Gauge No. 08008)
1973	0.85 km^2	1.95 km^2	1.64 km^2
Growth	2.32 km^2 (+273%)	2.09 km^2 (+107%)	1.90 km^2 (+116%)
1995	3.17 km^2	4.04 km^2	3.54 km^2
Growth	0.12 km^2 (+4%)	2.192 (+54%)	1.93 km^2 (+55%)
2000	3.29 km^2	6.23 km^2	5.47 km^2
Growth	0.10 km^2 (+3%)	2.32 km^2 (+37%)	1.37 km^2 (+25%)
2008	3.39 km^2	8.55 km^2	6.85 km^2

Table 2.1 Changes in Urban Development Extent 1973 - 2008

Area and urban extend (URBEXT)	Gauge Catchments		
	Owendoher at Willbrook Road (Gauge No. 09009)	Griffeen at Lucan (Gauge No. 09002)	Broadmeadow at Swords (Gauge No. 08008)
Total Area	22.6 km^2	35.0 km^2	108.0 km^2
Urban Fraction 1973	0.038	0.056	0.015
Urban Fraction 1995	0.140	0.115	0.033
Urban Fraction 2000	0.146	0.178	0.051
Urban Fraction 2008	0.150	0.244	0.063

Table 2.2 Changes in Urban Fraction 1973 - 2008

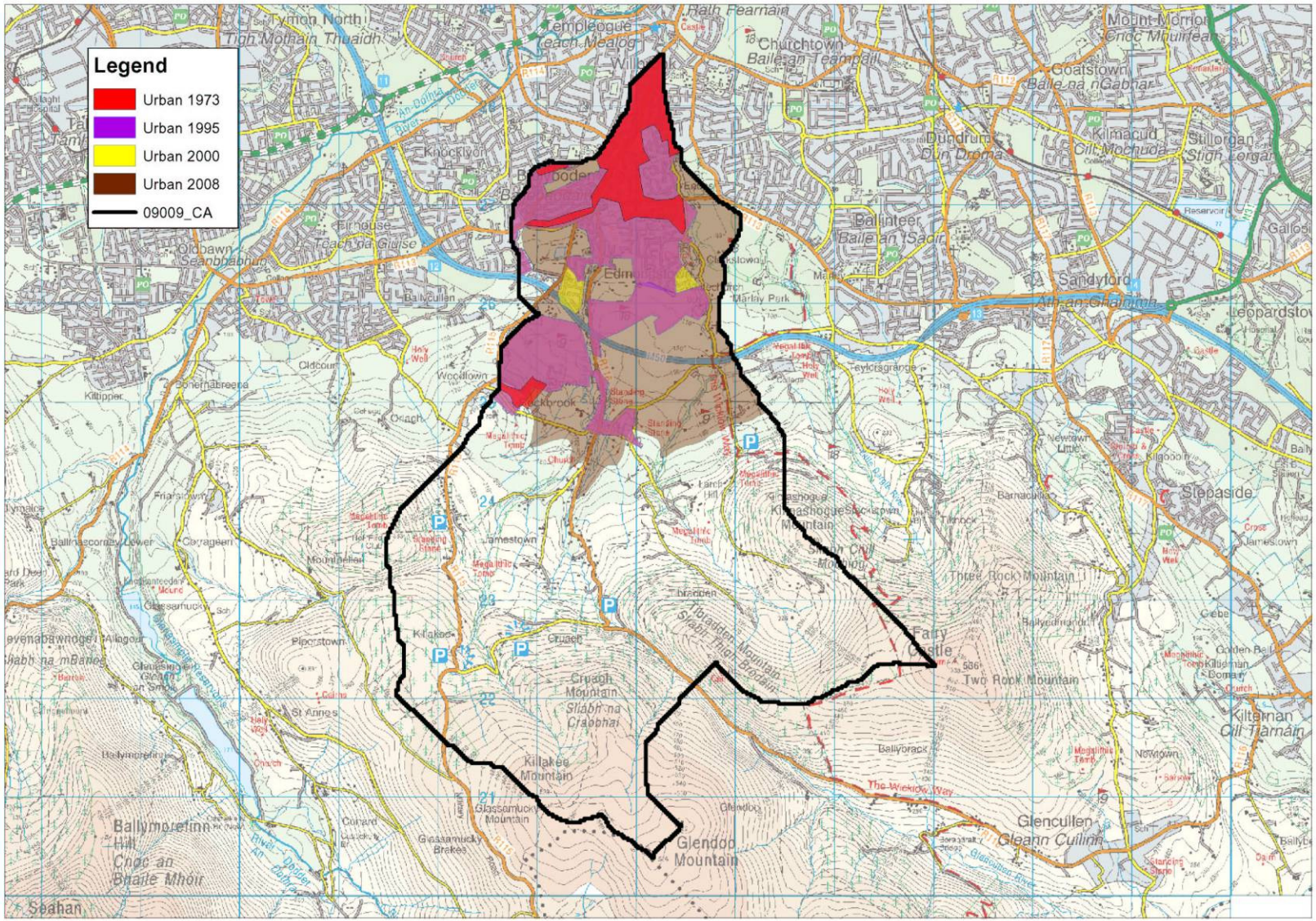


Figure 2-4 Owendoher Catchment – Changes in Urbanisation

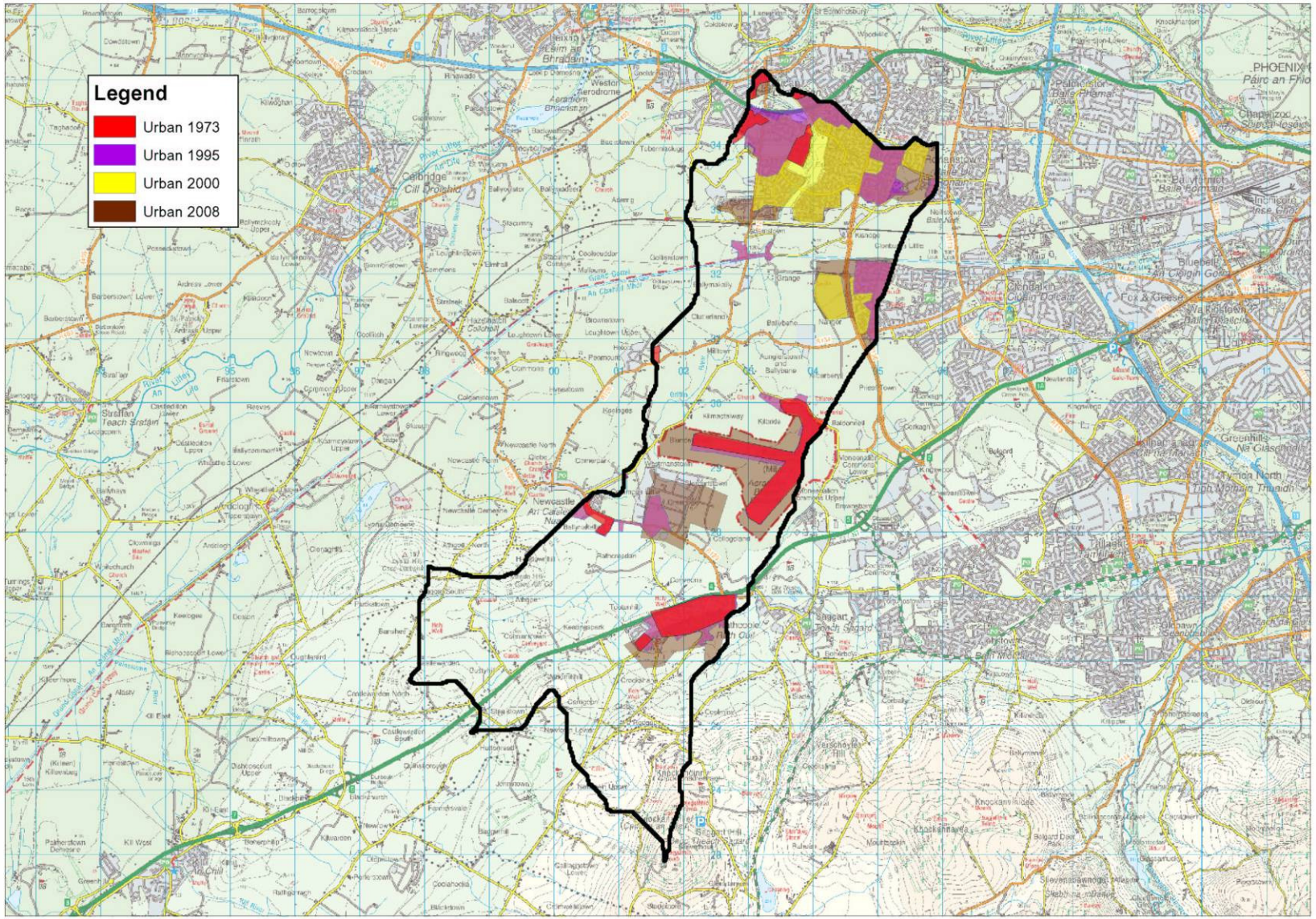


Figure 2-5 Griffeen Catchment – Changes in Urbanisation

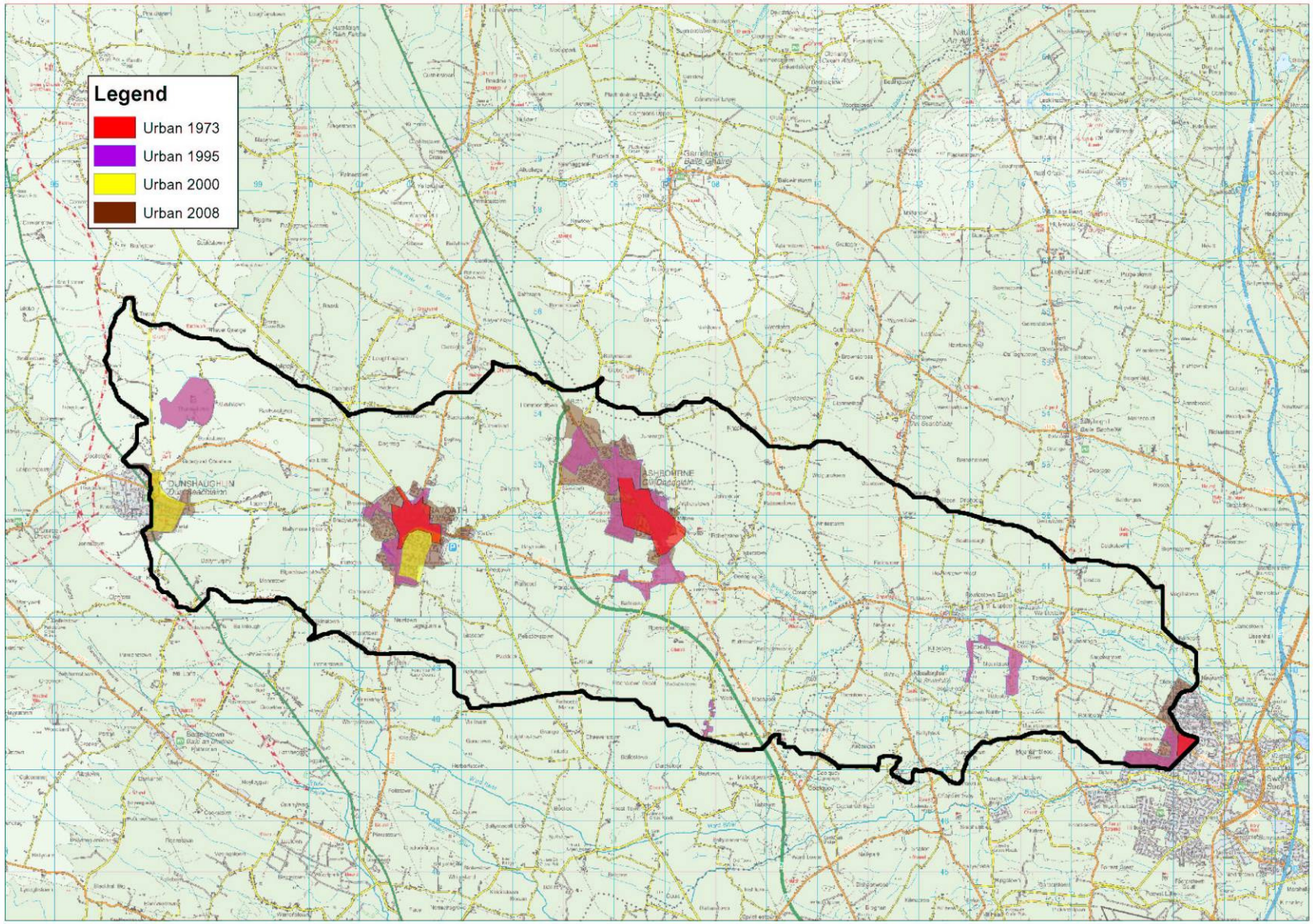


Figure 2-6 Broadmeadow Catchment – Changes in Urbanisation

3 ANALYSIS OF GAUGED RECORDS

3.1 TREND ANALYSIS OF GAUGED DISCHARGE RECORDS

A trend analysis was carried out on the discharge records for the three gauging stations selected for this study. The purpose of this analysis was to identify any change in peak discharge frequency in the gauge catchments which could be attributed to changes in urbanisation. Various preliminary statistical tests were undertaken on the data sets to identify the effects of urbanisation. Initially the data sets were analysed over the entire year, however after some consideration the data sets (both rainfall and discharge) were split into seasonal intervals and analysed separately for winter and summer periods. The rationale for this was driven by the high antecedent wetness and the low evaporation figures in general found in Ireland during winter months. It is argued that the low absorption and permeability of the largely water logged ground in rural areas during winter months is too similar to the urbanised areas in terms of runoff characteristics, in particular in the presence of arterial drainage. Thus the effects of urbanisation should be more prominent in summer months compared to winter months. As a result all the trend analysis on the gauged data was carried out on the seasonal data series.

The first step of the trend analysis was to extract the peak events from the discharge records at each of the gauging stations using peak over threshold analysis. This was completed for two separate average annual numbers of extreme events; 3 events per year and 5 events per year. Two frequencies were chosen to increase the robustness of the analysis. The average annual number of events may not mean that exactly 3 or 5 events are chosen per calendar year, but rather that the total number of events extracted is the equivalent to 3 or 5 per year. In other words, for the '3 event per year' analysis and a twenty year data set a threshold is set so that the highest 60 events are chosen but not necessarily 3 per calendar year. The peak events were extracted for the summer (April - September) and winter (October - March) months separately to identify any seasonal trends. Histograms were produced of the seasonally extracted peak events with the data divided into time interval bins. Two separate time interval bin periods were chosen for each histogram, again to improve the robustness of the analysis.

The entire discharge record at each of the gauging stations was examined for data gaps. When identified, the data gap periods were noted and the histogram bins containing the data gaps identified. The numbers of events in the effected bins were then adjusted proportionally to take account of the missing data. The histograms bins were then normalised and re-plotted.

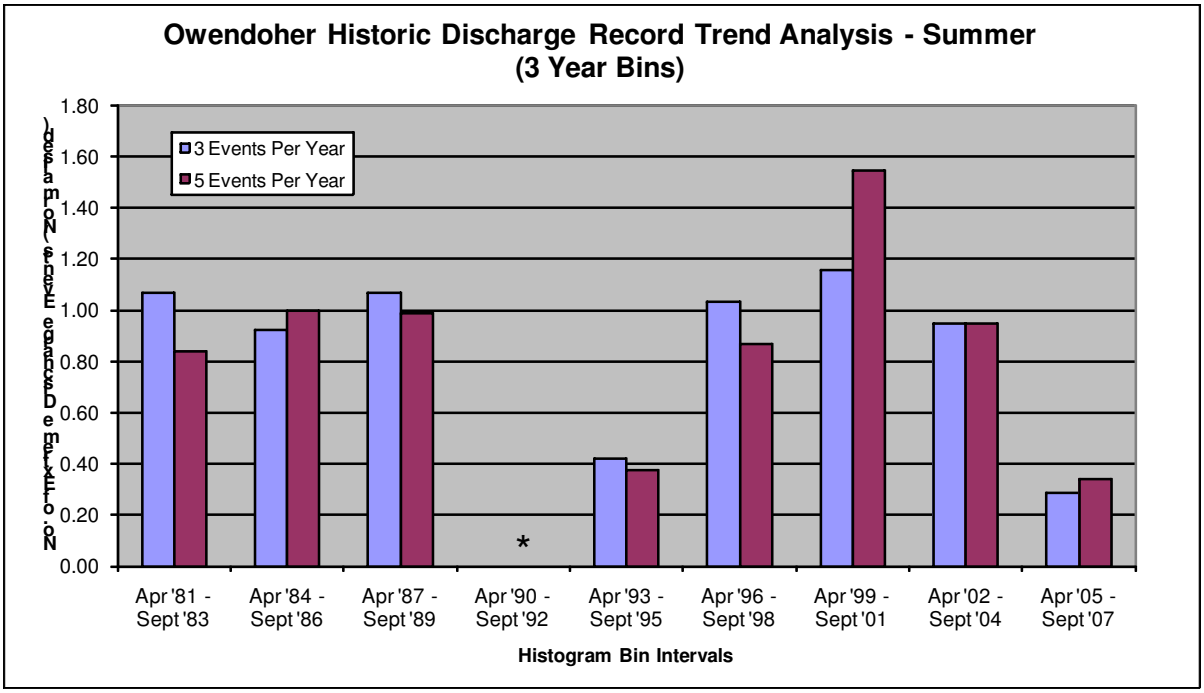
The graphs were normalised to allow direct comparison between the different annual average numbers of extreme events extracted from the data sets. The vertical axis on the figures presented in this section represents the normalised number of extreme events, i.e.:

- For the "3 Event Per Year" data set and "3 Year Bin Intervals", a normalised value of 1 on the bar chart corresponds to 3 x 3 = 9 extreme events;
- For the "5 Event Per Year" data set and "3 Year Bin Intervals", a normalised value of 1 on the bar chart corresponds to 5 x 3 = 15 extreme events;
- For the "3 Event Per Year" data set and "5 Year Bin Intervals", a normalised value of 1 on the bar chart corresponds to 3 x 5 = 15 extreme events;
- For the "5 Event Per Year" data set and "5 Year Bin Intervals", a normalised value of 1 on the bar chart corresponds to 5 x 5 = 25 extreme events.

The trend analysis data and results for each of the number of events at each of the three gauging stations are provided below. A trend analysis of flood magnitudes was also undertaken, a brief discussion on the findings is given at the end of this section.

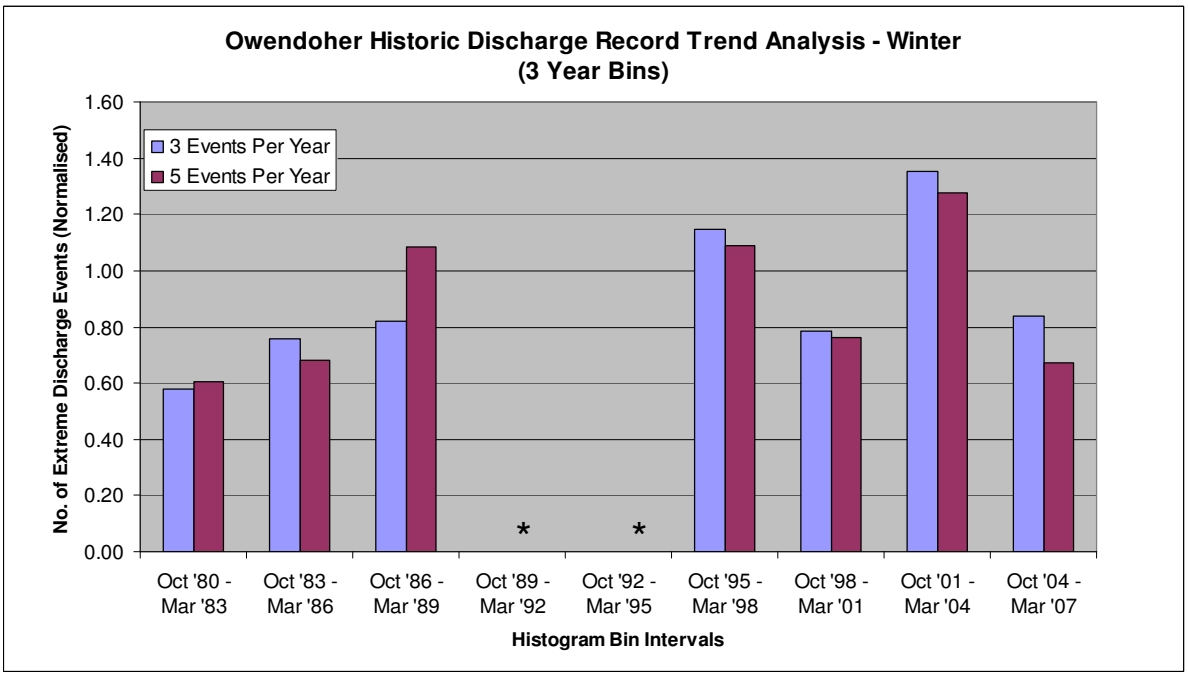
3.1.1 Owendoher at Willbrook Road (Gauge No. 09009)

Gauged discharge records were made available by the EPA for the period 1980 to 2007 as detailed in Section 1.1.1.2. The total length of data gaps within this record equate to approximately 7.2 years. The extracted peak discharge events from this gauge record have been plotted for the 3 per year and 5 per year summer and winter scenarios in Appendix B. The corresponding trend analysis histograms are shown here as follows:



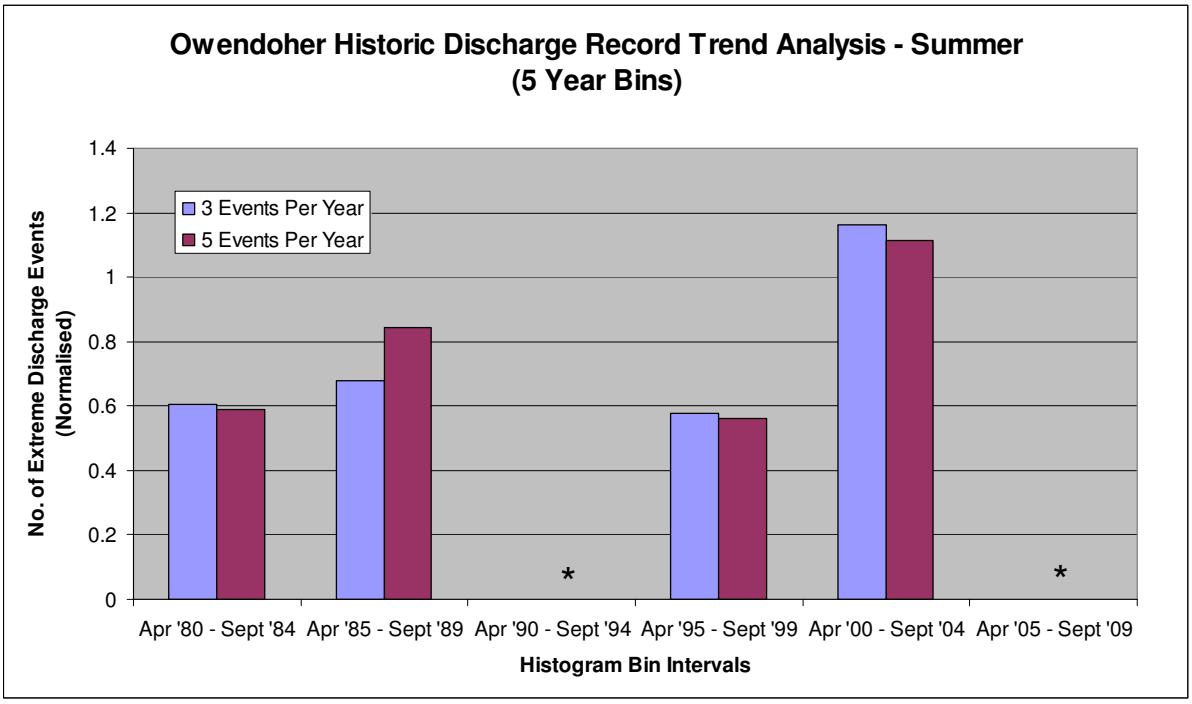
* Data gaps account for > 50% of histogram bin interval - bar graph removed.

Figure 3-1 Owendoher at Willbrook Road Discharge Trend Analysis – Summer (3 Year Bins)



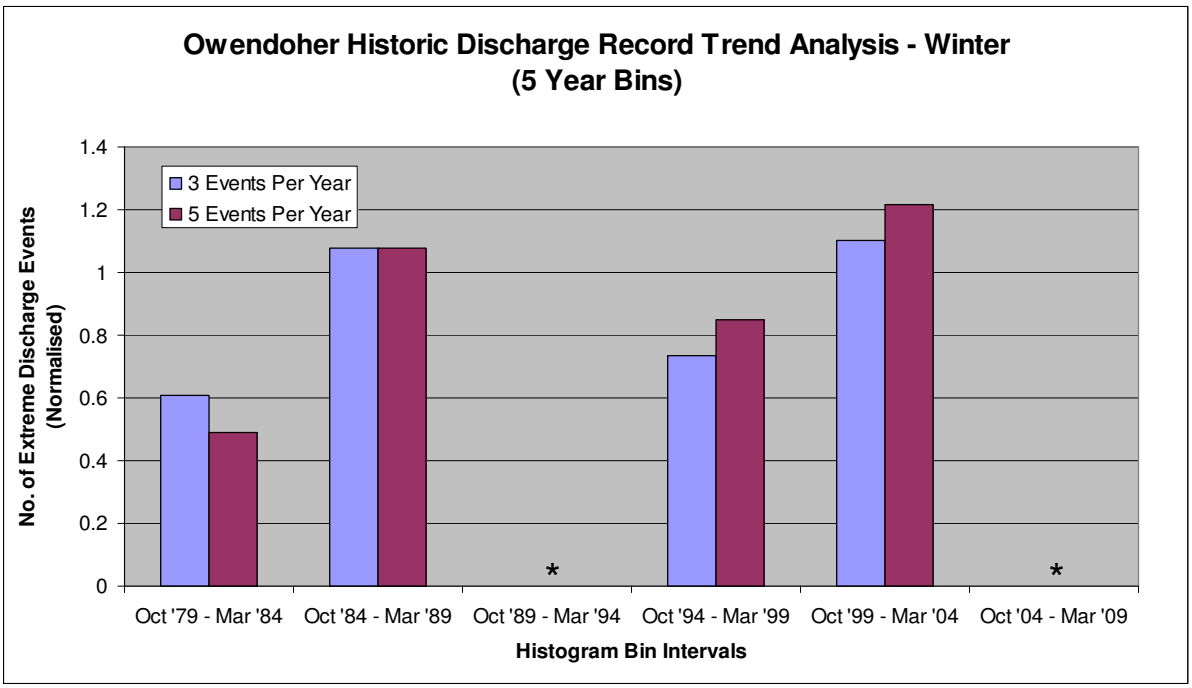
* Data gaps account for > 50% of histogram bin interval - bar graph removed.

Figure 3-2 Owendoher at Willbrook Road Discharge Trend Analysis – Winter (3 Year Bins)



* Data gaps account for > 50% of histogram bin interval - bar graph removed.

Figure 3-3 Owendoher at Willbrook Road Discharge Trend Analysis – Summer (5 Year Bins)



* Data gaps account for > 50% of histogram bin interval - bar graph removed.

Figure 3-4 Owendoher at Willbrook Road Discharge Trend Analysis – Winter (5 Year Bins)

3.1.1.1 Comment

Visual inspection of the trend analysis histograms of gauged discharge records at Willbrook Road indicates that there is no apparent trend towards an increased number of extreme discharge events over time. The presence of large gaps in the data series however limits confidence in this observation as it limits the number of available bins for comparison thus making the identification of any trend more difficult.

The absence of an obvious trend in the Owendoher summer and winter data sets is attributed to the relative changes in urbanisation over time. The major increase in urban area in this catchment occurred between 1973 and 1995 and equates to an increase of approximately 10% while between 1995 and 2008 there was only a marginal increase in urban area of approximately 1%. The gauged discharge data used in this analysis stretches from 1980 to 2007 and given the absence of an identifiable trend it is suggested that the large urban expansion occurred prior to or shortly after 1980.

In addition a significant portion of recent urban development has occurred in the upper reaches of the catchment on high steep ground. Higher ground will traditionally have shallow bed-rock and steep slopes which produce an “urban-type” runoff response to catchment rainfall. Therefore urban development in this area may not produce a significant change in catchment runoff.

3.1.2 Griffeen at Lucan (Gauge No. 09002)

Gauged water level records were made available by the EPA for the period 1977 to 2008 as detailed in Section 1.1.2.2. The water levels from 1977 to 2002 were converted to discharges using Hydro Environmental’s rating curve while those levels from 2004 to 2008 were converted to discharges using the rating curve developed from a hydraulic model of the gauge site constructed for this study. The discharge records were then combined to make a near continuous data set from 1977 to 2008. The total length of data gaps within this record equates to approximately 3.3 years. The extracted peak discharge events from this gauge record have been plotted for the summer and winter 3 per year and 5 per year scenarios and are presented in Appendix B. The trend analysis histograms are shown here as follows:

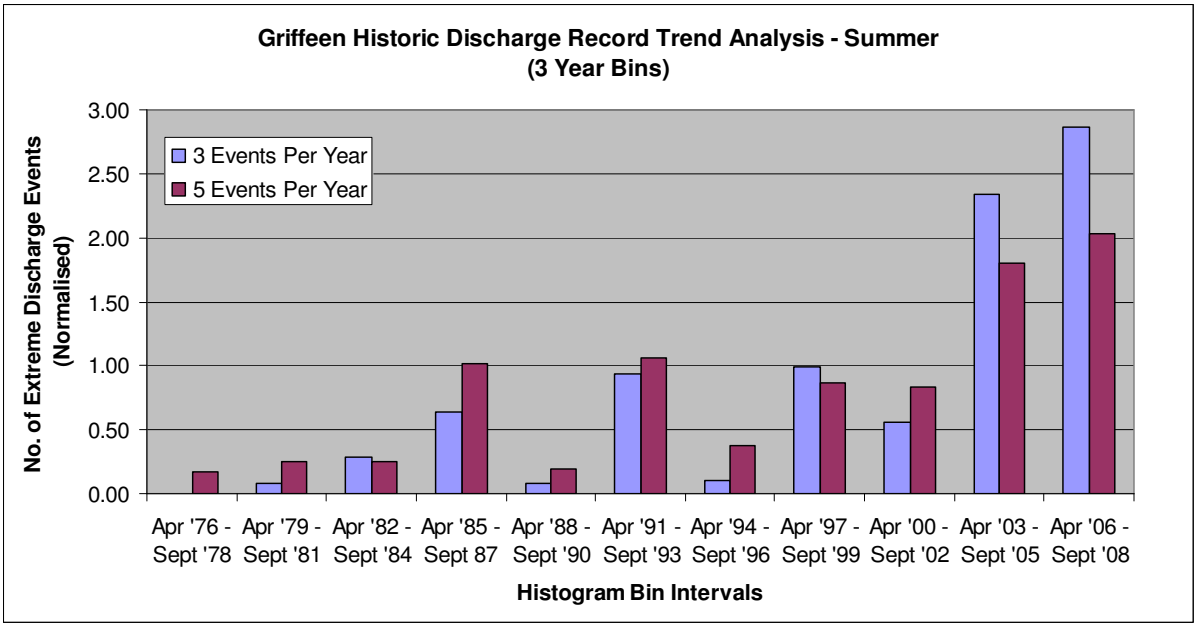


Figure 3-5 Griffeen at Lucan Discharge Trend Analysis – Summer (3 Year Bins)

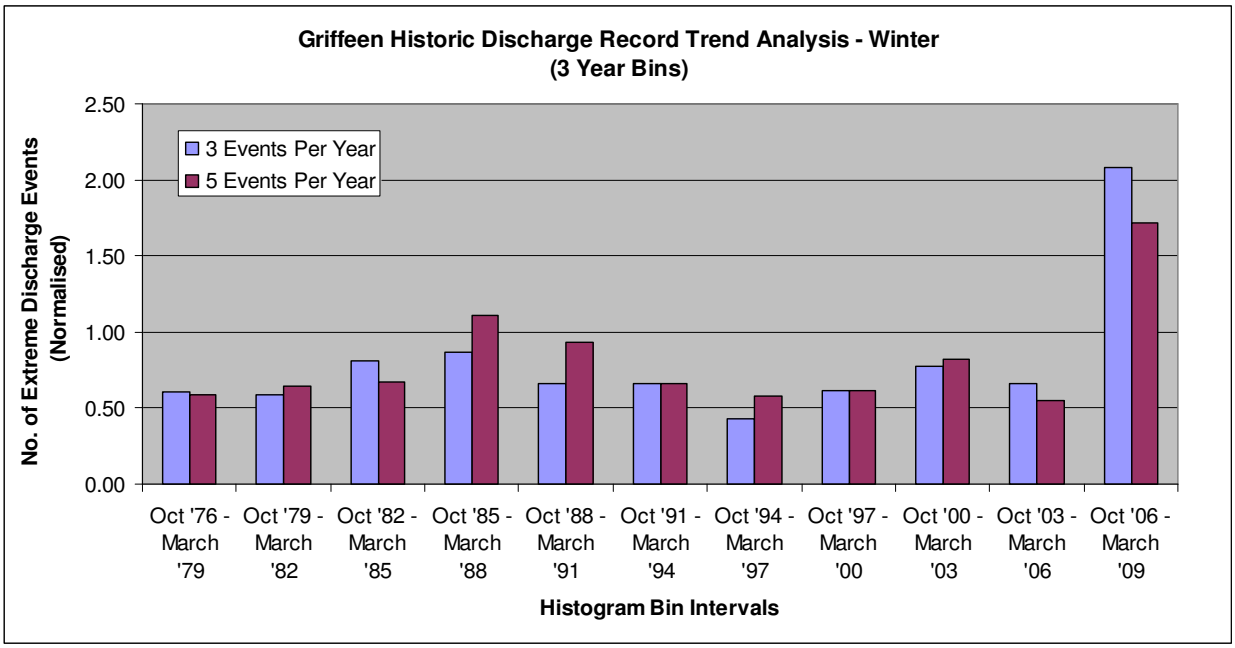


Figure 3-6 Griffeen at Lucan Discharge Trend Analysis – Winter (3 Year Bins)

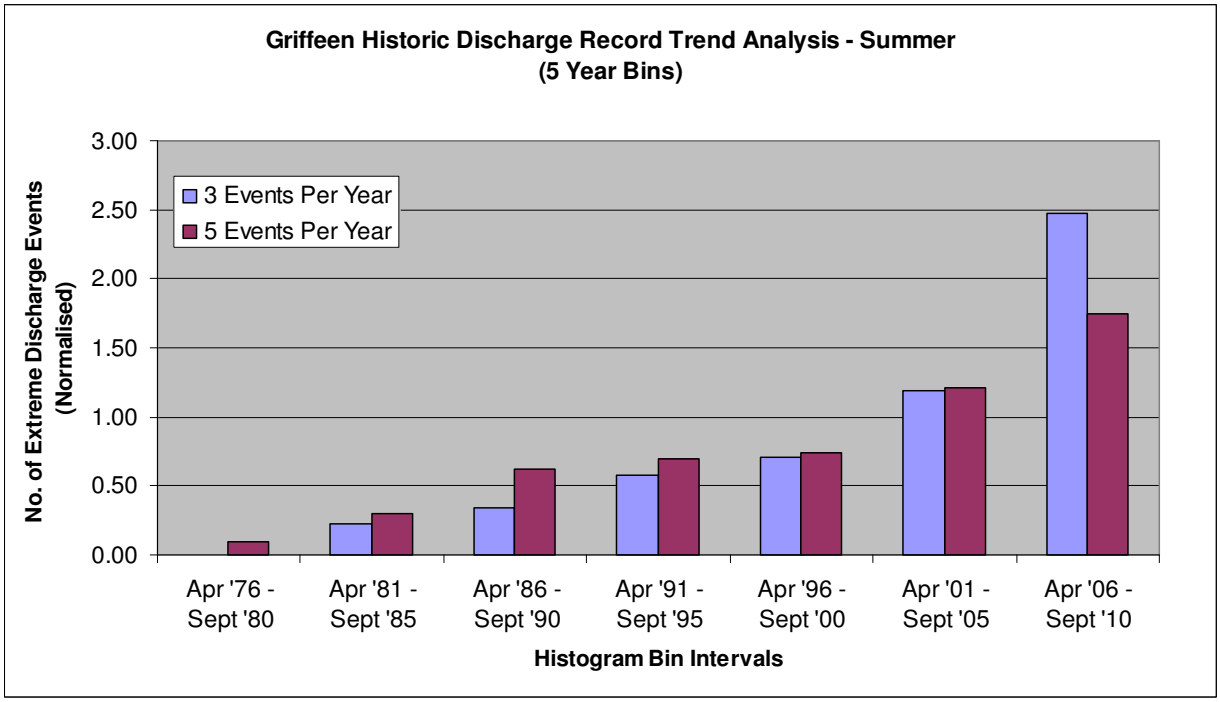


Figure 3-7 Griffeen at Lucan Discharge Trend Analysis – Summer (5 Year Bins)

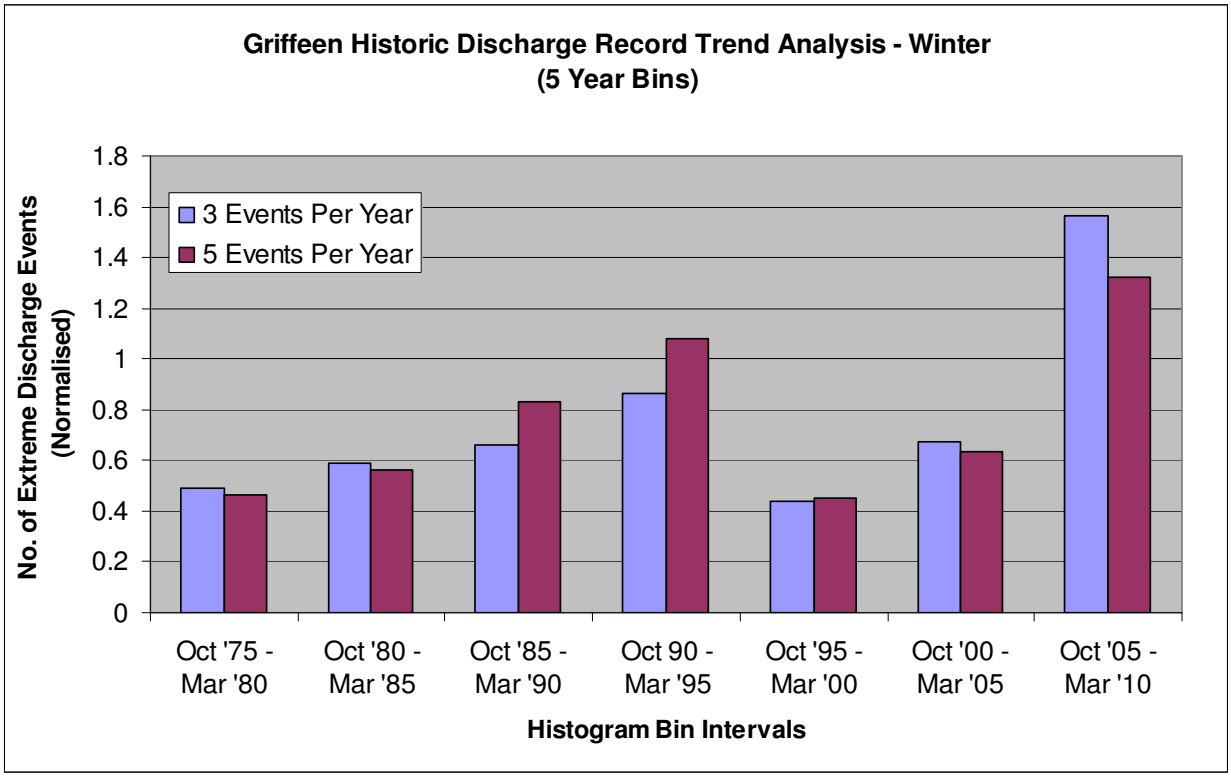


Figure 3-8 Griffeen at Lucan Discharge Trend Analysis – Winter (5 Year Bins)

3.1.2.1 Comment

A trend towards increased extreme discharge event frequency over time can be seen in the summer season trend analysis histograms from the Griffeen at Lucan (Figure 3-5 and Figure 3-7) particularly Figure 3-7**.** However there is no such obvious trend in the winter season trend analysis histograms (Figure 3-6 and Figure 3-8) except for a large increase in frequency in the last histogram bin. This increase may be attributable to the flood alleviation works carried out on the river channel in the vicinity of the gauging station site circa. 2004 as it can also be seen in the summer season histograms.

The trend identified in the Griffeen summer data set is generally deemed to be due to the increased urbanisation seen in the Griffeen gauge catchment, although the marked increase over the more recent years may be influenced by the flood alleviation works. The increasing urban or impermeable surface area over time creates greater peak run-off which shows itself in increased discharge peaks in the Griffeen River. The trend is present in both the ‘3 event per year’ and ‘5 event per year’ data sets which gives increased weight to the judgement. The lack of trend in the winter data-set can probably be attributed to antecedent soil conditions in that the soil over the entire catchment may be saturated for much of the time during the winter months producing run-off conditions similar to those of an impermeable surface. Therefore the impact of increased urbanisation is less obvious in the discharge records for the winter period.

3.1.3 Broadmeadow at Swords (Gauge No. 08008)

Gauged water level records were made available by the OPW for the period 1977 to 2008 as detailed in Section 1.1.3.2. These water levels were converted to discharges using a rating curve generated from flow and level measurements taken by the OPW at this site. The data gaps within this record length equate to approximately 1.1 years. The extracted peak discharge events from this gauge record have been plotted for the summer and winter 3 per year and 5 per year scenarios and are presented in Appendix B. The trend analysis histograms are shown here as follows:

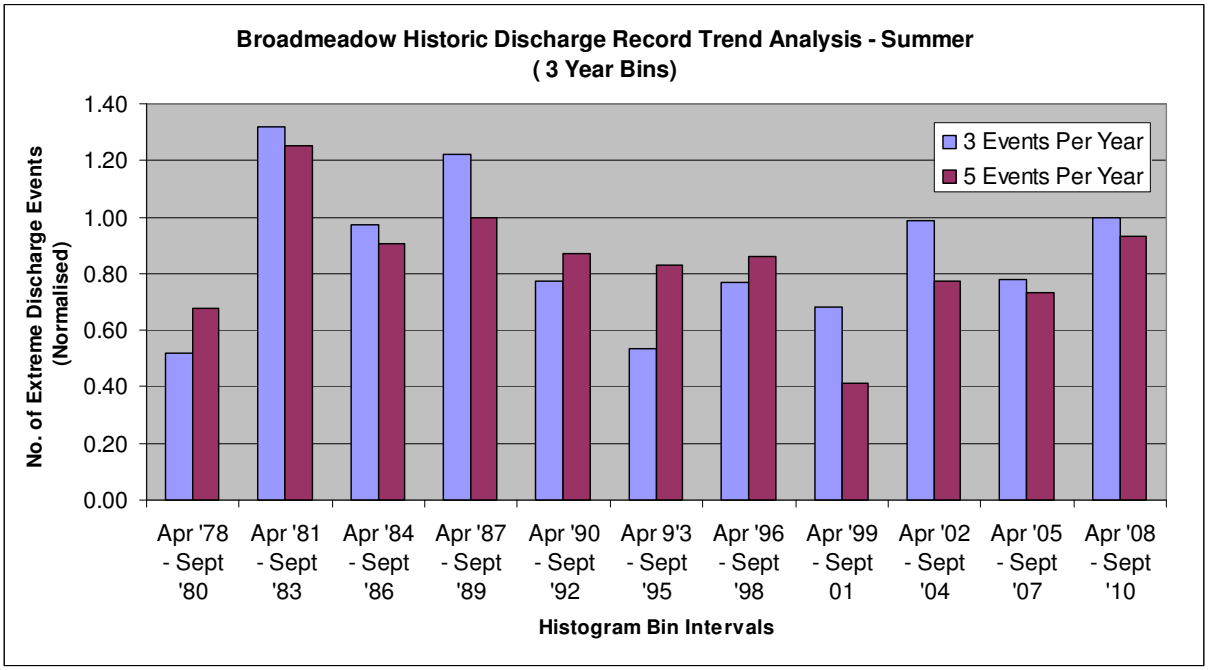


Figure 3-9 Broadmeadow at Swords Discharge Trend Analysis – Summer (3 Year Bins)

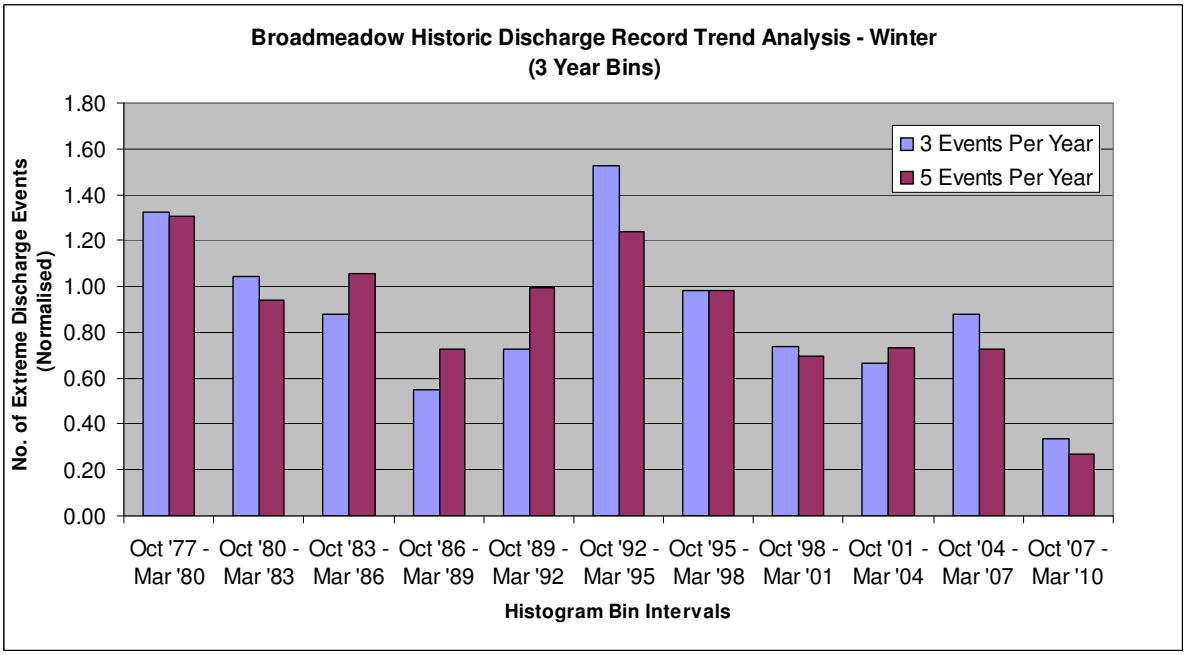


Figure 3-10 Broadmeadow at Swords Discharge Trend Analysis – Winter (3 Year Bins)

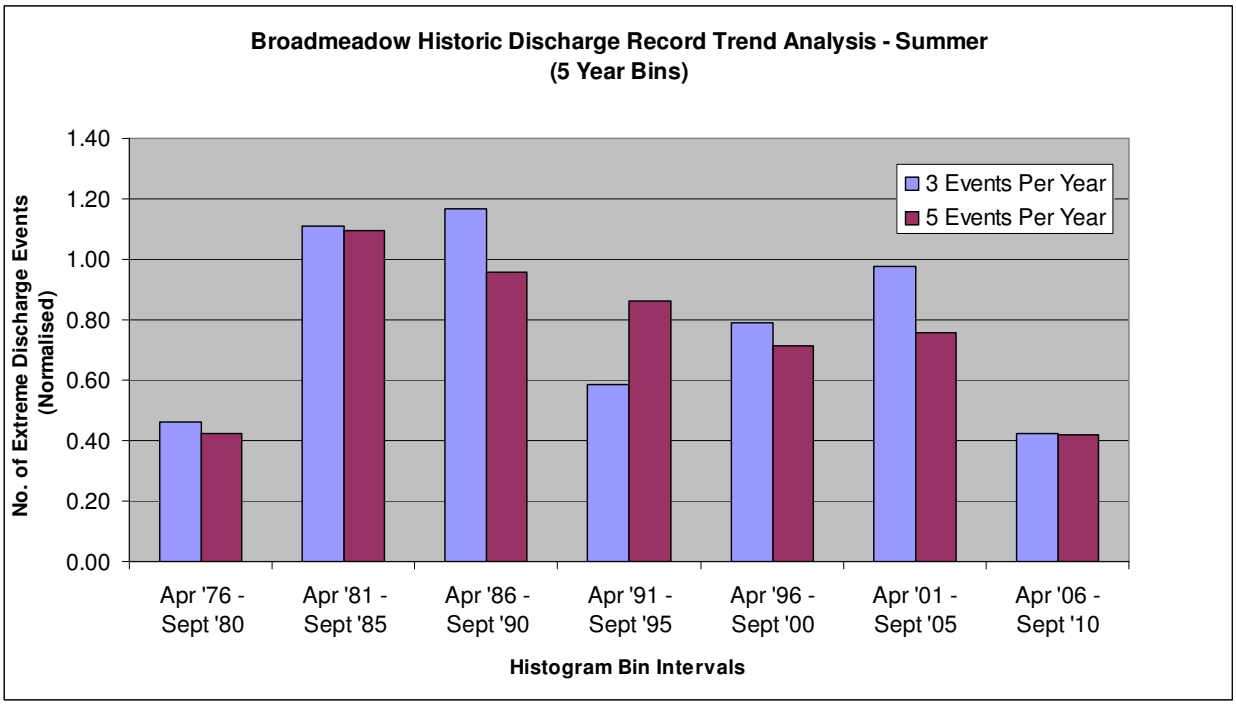


Figure 3-11 Broadmeadow at Swords Discharge Trend Analysis – Summer (5 Year Bins)

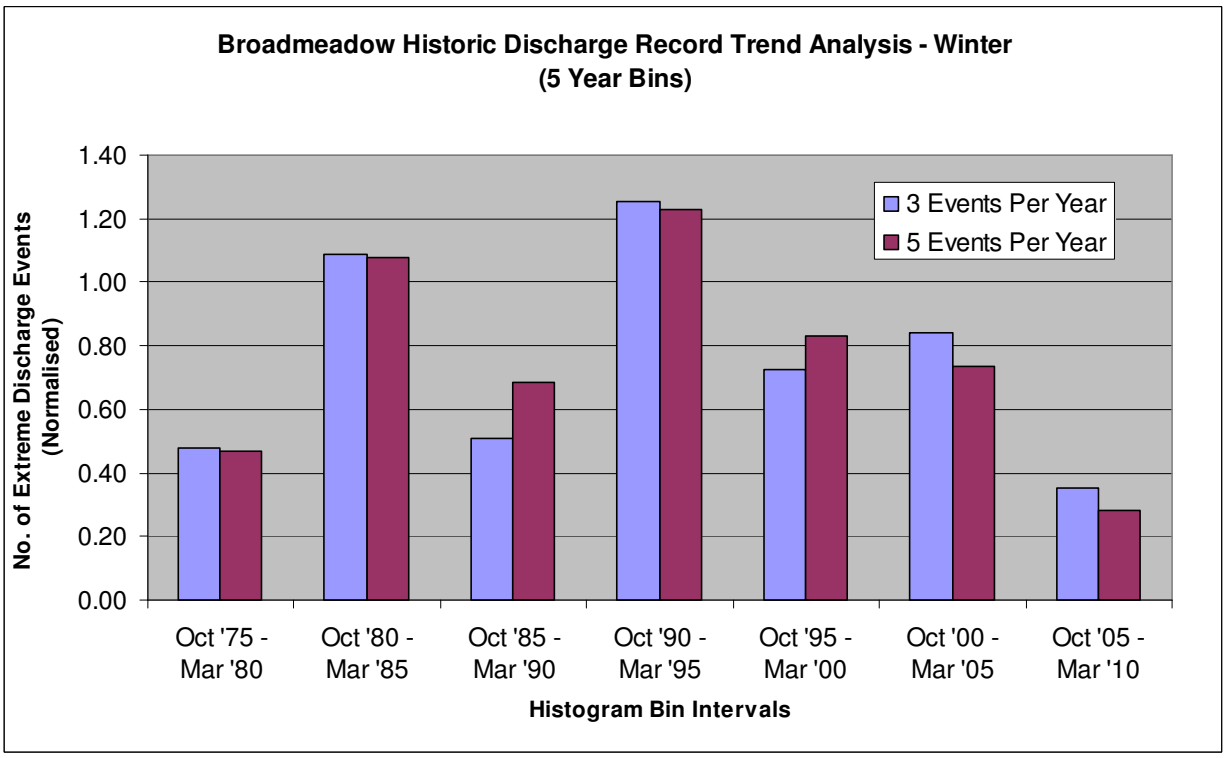


Figure 3-12 Broadmeadow at Swords Discharge Trend Analysis – Winter (5 Year Bins)

3.1.3.1 Comment

Visual examination of the trend analysis histograms of gauged discharge records on the Broadmeadow River indicates that there is no apparent trend towards an increased number of extreme discharge events over time.

The absence of an obvious trend in the Broadmeadow summer and winter data sets is attributed to the relatively small size of the urbanised area to the overall catchment area. The urban areas within the Broadmeadow gauge catchment only account for approximately 6% of the overall catchment area and the impact of the increased impermeable surface is thought to be diluted by the larger greenfield run-off. In addition, the majority of the urban development is located at a distance from the gauging station site which increases the difficultly in identifying any discernable change in runoff response due to hydrograph attenuation within the river system.

3.1.4 Trend analysis of gauged flow data by flow magnitude

The previous section explored the change in frequency of events to ascertain the presence or absence of trends. This method is used when the changes as a result of trend are not necessarily causing an overall increase in the flood magnitude. The practise of using the magnitude of the events to establish the presence of trends is more common in trend analysis and this was initially pursued in this study. However the analysis was largely inconclusive, in fact in certain instances it could be argued that there was a negative trend or positive trend depending whether or not the most recent (2007-2010) runoff events were included or not. It might seem that this weakens the argument as to the presence of trends, if the analysis of flood magnitudes is inconclusive. However the difficulty in this case is that with the percentage of urbanisation found in the test catchments very large flood events are unlikely to be significantly affected by urbanisation. It can be argued that these flood events occur with high antecedent wetness when parts of the rural catchment, in particular those with arterial drainage react similarly to urbanised areas. The numerical modelling presented in the latter part of this report supports this and as a result the trend analysis of flood magnitude was not further pursued in this study.

3.2 TREND ANALYSIS OF GAUGED RAINFALL RECORDS

A trend analysis was carried out on the gauged rainfall records from stations within or adjacent to each of the hydrometric gauge catchments selected for this study. This analysis was undertaken to identify whether any trends in discharge data could be attributed to trends in catchment rainfall. The data is presented in the same format as the discharge trend analysis in the previous chapter. Thus the hourly rainfall records have been split into winter and summer season and two different bin sizes as well as two different numbers of events per year. As the time to peak of each catchment investigated in this study is greater than one hour, it could be argued that hourly rainfall trend analysis is not strictly relevant, as longer period events would primarily be contributing to the extreme events recorded at the gauging stations. Thus a separate trend analysis of the rainfall covering the entire catchment has been completed as shown at the end of each section. This covers the 1 hourly, 2 hourly, 3 hourly 6 hourly ½ daily and daily accumulated rainfall values based on hourly accumulations. In the peak over threshold analysis the largest event in each time series has been extracted regardless of the actual start or end of the event. An independence criterion was chosen to ensure that events were not overlapping or the result of the same storm event. This independence criterion selected events that were at least 24 hours apart and in addition where the total rainfall in between the previous peak and the new peak value had fallen below 50 percent of the preceding peak. This ensures that events are selected that do not originate from the same rainfall storm event and thus can be considered statistically independent.

3.2.1 Owendoher at Willbrook Road (Gauge No. 09009)

The rainfall data used in the analysis of the Owendoher gauge records at Willbrook Road was that from the representative rainfall file produced for the River Dodder CFRAMS. A trend analysis was

undertaken on the hourly rainfall depths from this file for the period 1980 to 2007 and the results are presented in, Figure 3-13 to Figure 3-16 below. Figure 3-17 shows the results of the trend analysis for the assimilated catchment wide rainfall data of various durations based on the entire available rainfall data set.

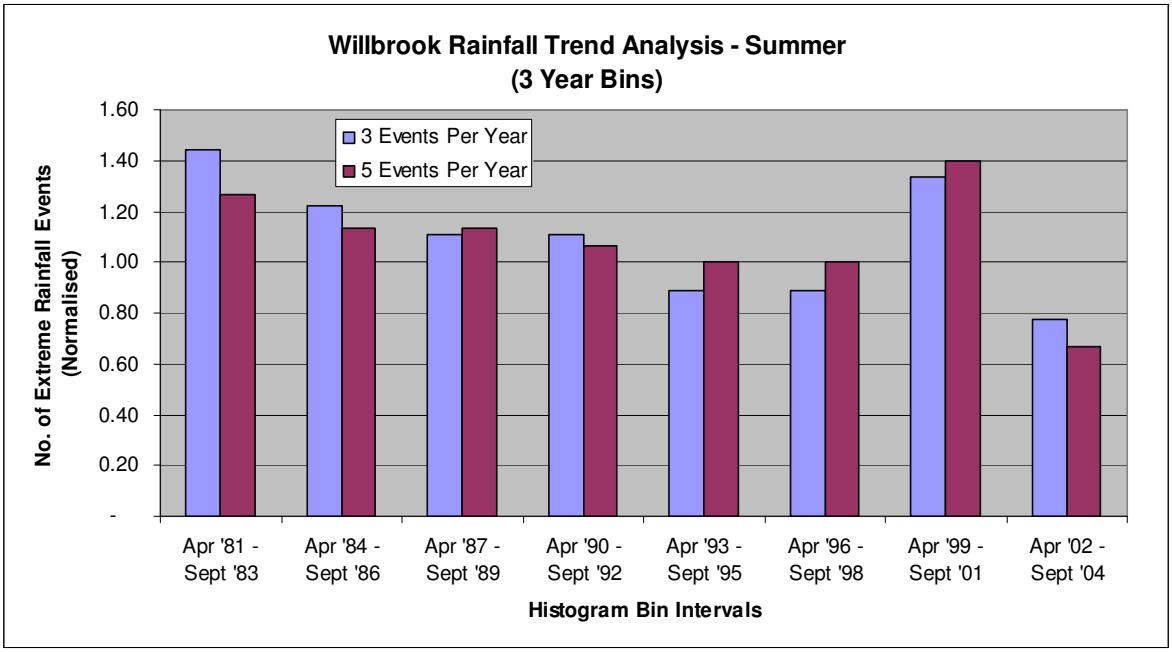


Figure 3-13 Willbrook Rainfall Trend Analysis – Summer (3 Year Bins)

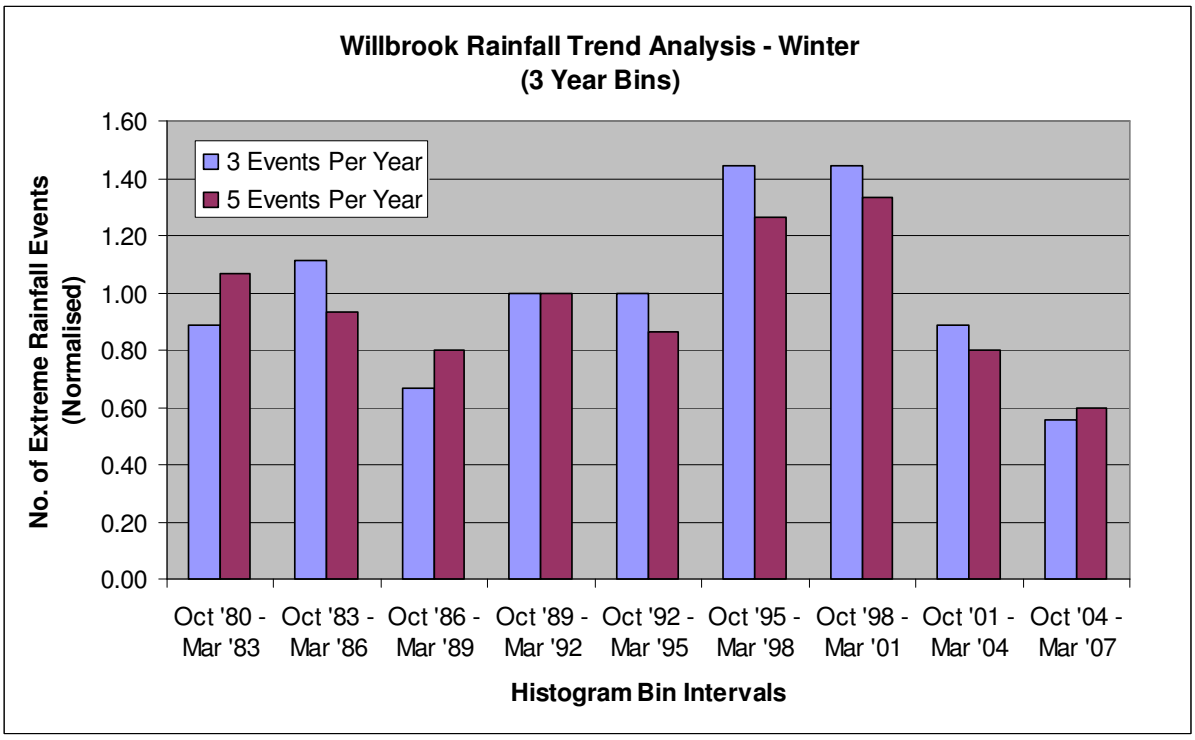


Figure 3-14 Willbrook Rainfall Trend Analysis – Winter (3 Year Bins)

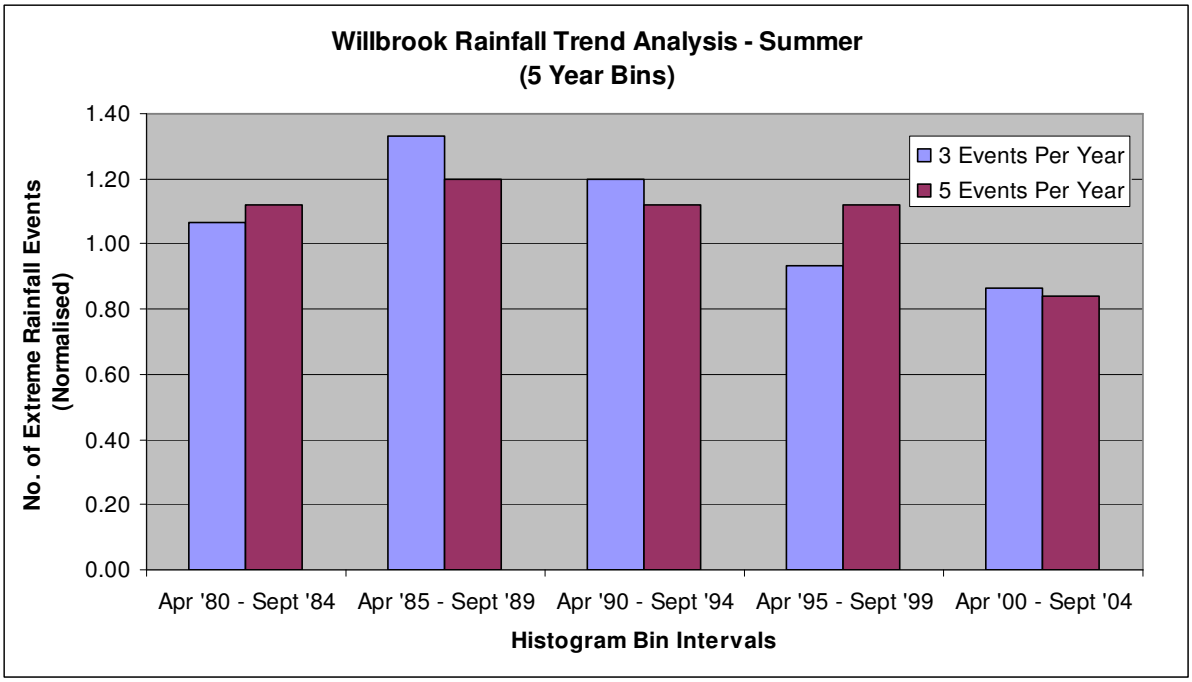


Figure 3-15 Willbrook Rainfall Trend Analysis – Summer (5 Year Bins)

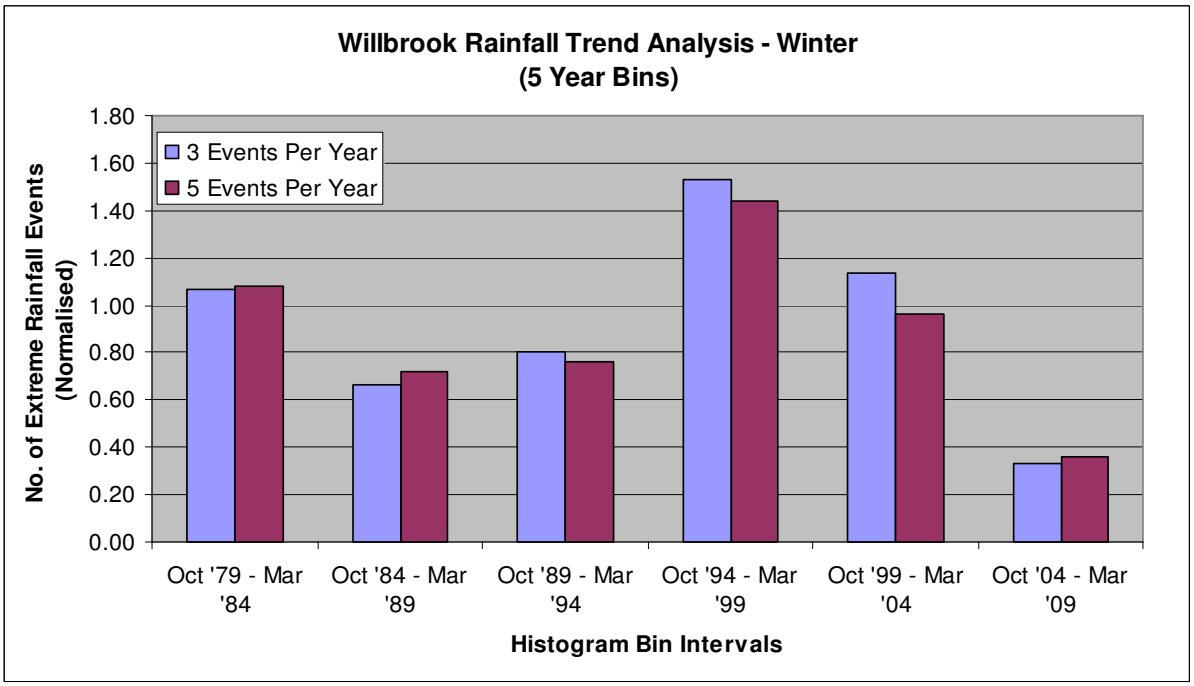


Figure 3-16 Willbrook Rainfall Trend Analysis – Winter (5 Year Bins)

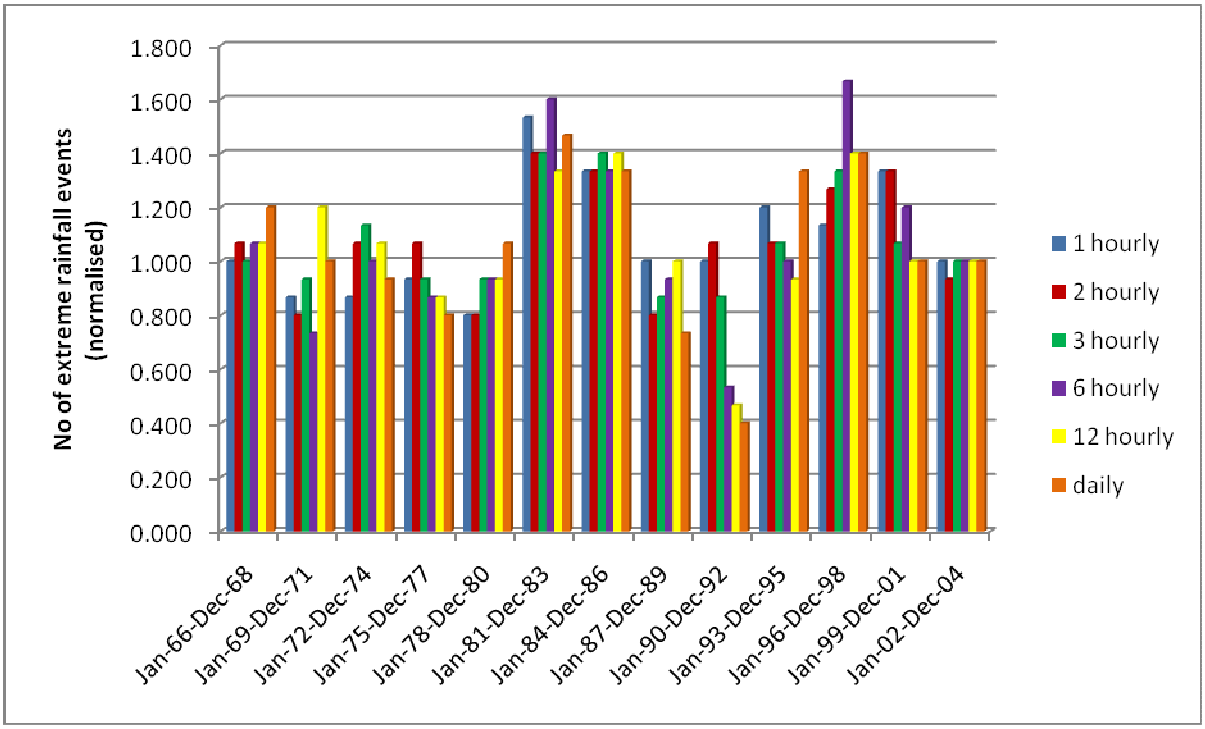


Figure 3-17 Rainfall Trend Analysis for entire catchment of Owendoher choosing different accumulation periods, 5 events per year and 3 year bins

3.2.1.1 Comment

The extreme rainfall occurrence trend analysis undertaken in this study shows considerable variation in the number of extreme rainfall events occurring from year to year. However there is no obvious trend towards increased numbers of extreme rainfall events over time in the time scale examined. Changing the duration of the rainfall examined also does not indicate a significant trend in the average number of occurrences, in general the correlation between events of different duration is relatively high (Figure 3-17). The analysis does however suggest a possible trend for increasing variability in the number of events per year, i.e. years with several extreme rainfall events followed by years with a lower number of extreme events may be becoming more common. It can also be seen that the period of 1984 to 1986 is not outstanding even though the largest event on record (Hurricane Charlie, 25/08/1986) falls in this period. It is not quite clear why this is the case as the event was recorded on both the Casement and Dublin Airport rain gauges. Also it lead to considerable flooding in the Dodder catchment, of which the Owendoher is part, yet was less severe in other Dublin catchments. Mass balance analysis of gauging records on the river Dodder gauging station and the upstream rainfall records suggest a mismatch in water balance for this event, which is quite likely due to erroneous recordings of the rainfall gauges possibly due to overtopping as has been indicated by other authors (*pers comm Micheal McCarthy*). In addition while all other streams leading to the Dodder were in flood with considerable damages during the Hurricane Charlie event, according to anecdotal evidence the Owendoher was not that severely hit. Unfortunately the discharge gauging station was put in place after the event, thus no gauging records exits for this period.

3.2.2 Griffeen at Lucan (Gauge No. 09002)

The rainfall data used in the analysis of the Griffeen gauge records at Lucan are those from Casement Aerodrome Met Eireann synoptic station. A trend analysis was undertaken on the hourly rainfall depths from this station for the period 1977 to 2008 and the results are presented in Figure 3-18 to Figure 3-21. Figure 3-22 shows the results of the trend analysis for the assimilated catchment wide rainfall data of various durations based on the entire available rainfall data set.

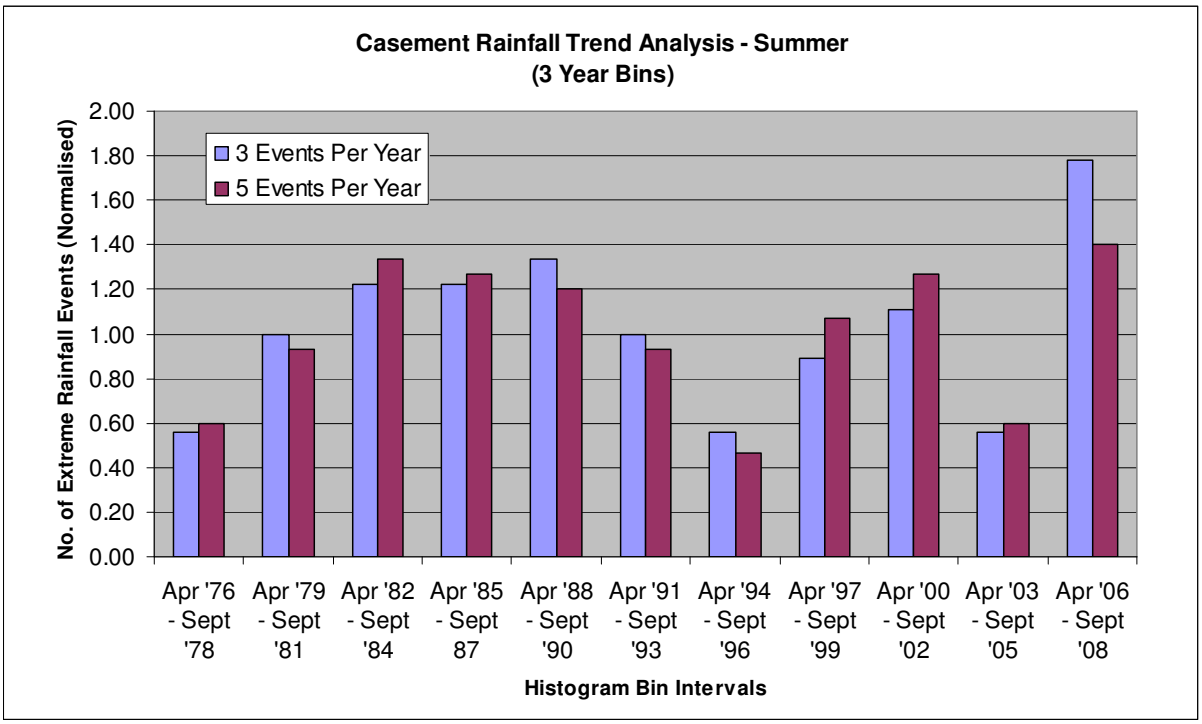


Figure 3-18 Casement Rainfall Trend Analysis – Summer (3 Year Bins)

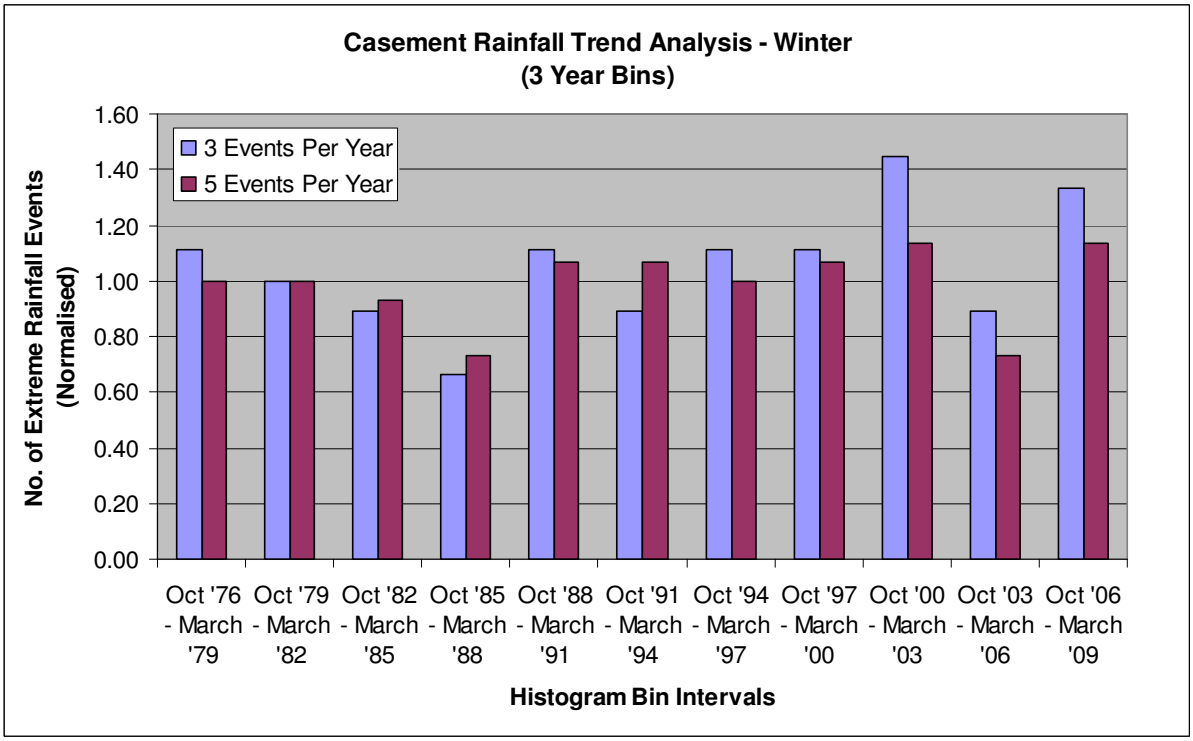


Figure 3-19 Casement Rainfall Trend Analysis – Winter (3 Year Bins)

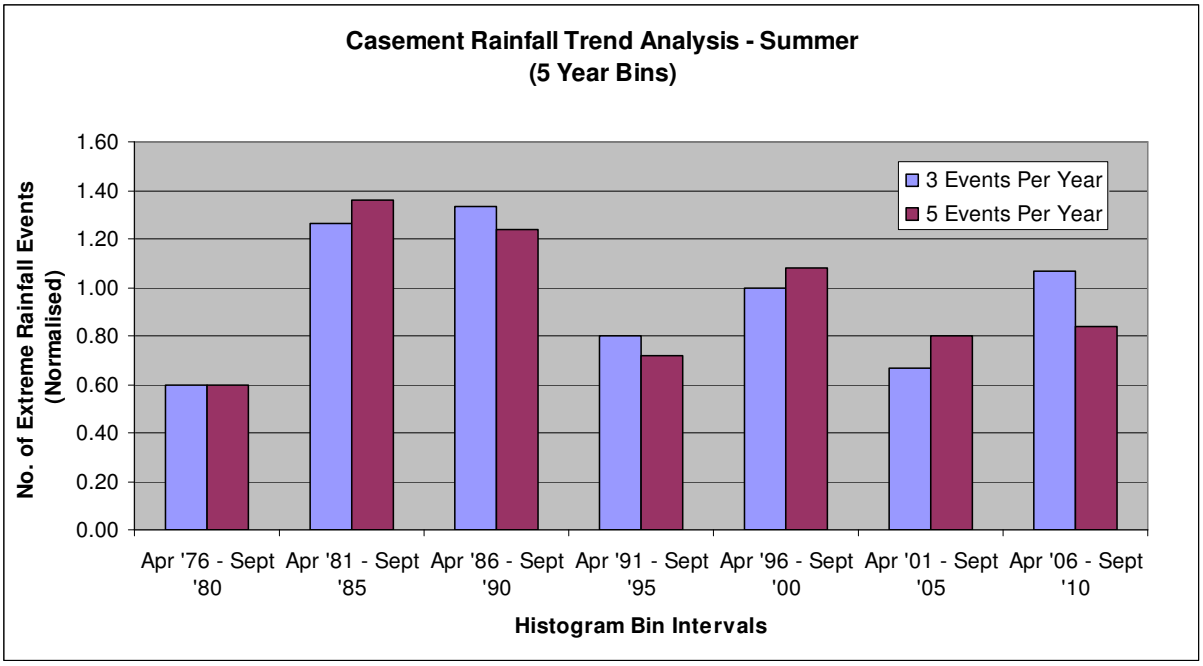


Figure 3-20 Casement Rainfall Trend Analysis – Summer (5 Year Bins)

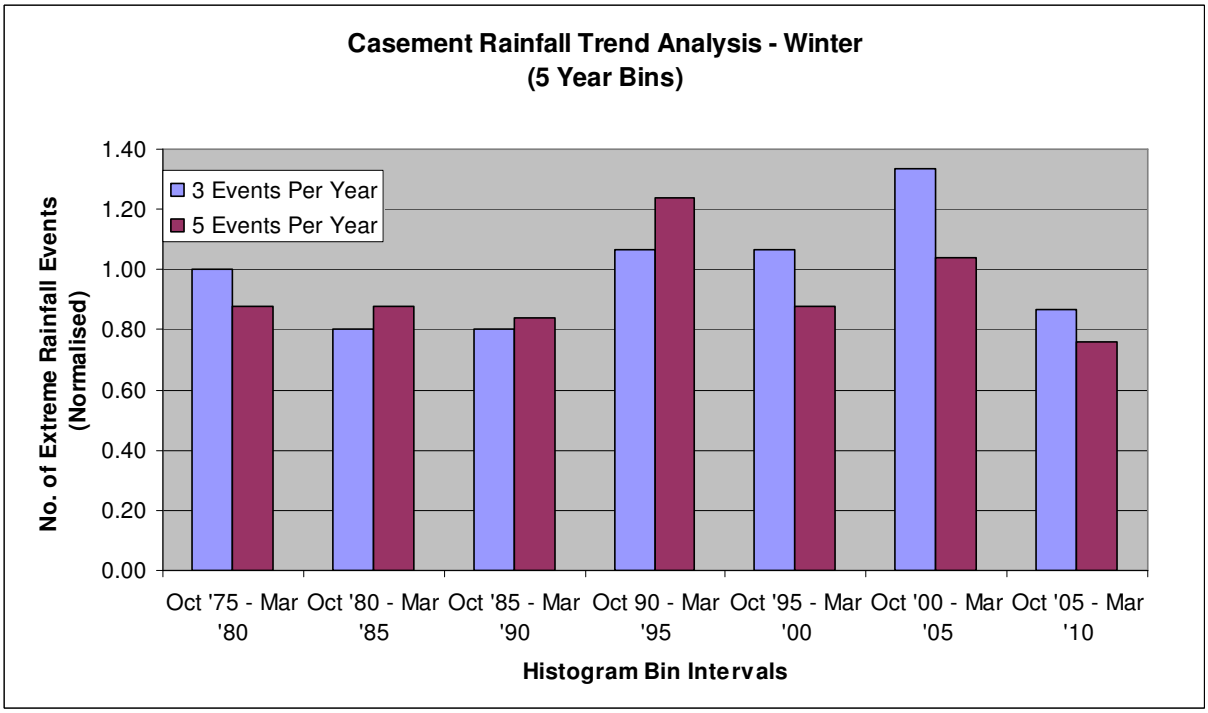


Figure 3-21 Casement Rainfall Trend Analysis – Winter (5 Year Bins)

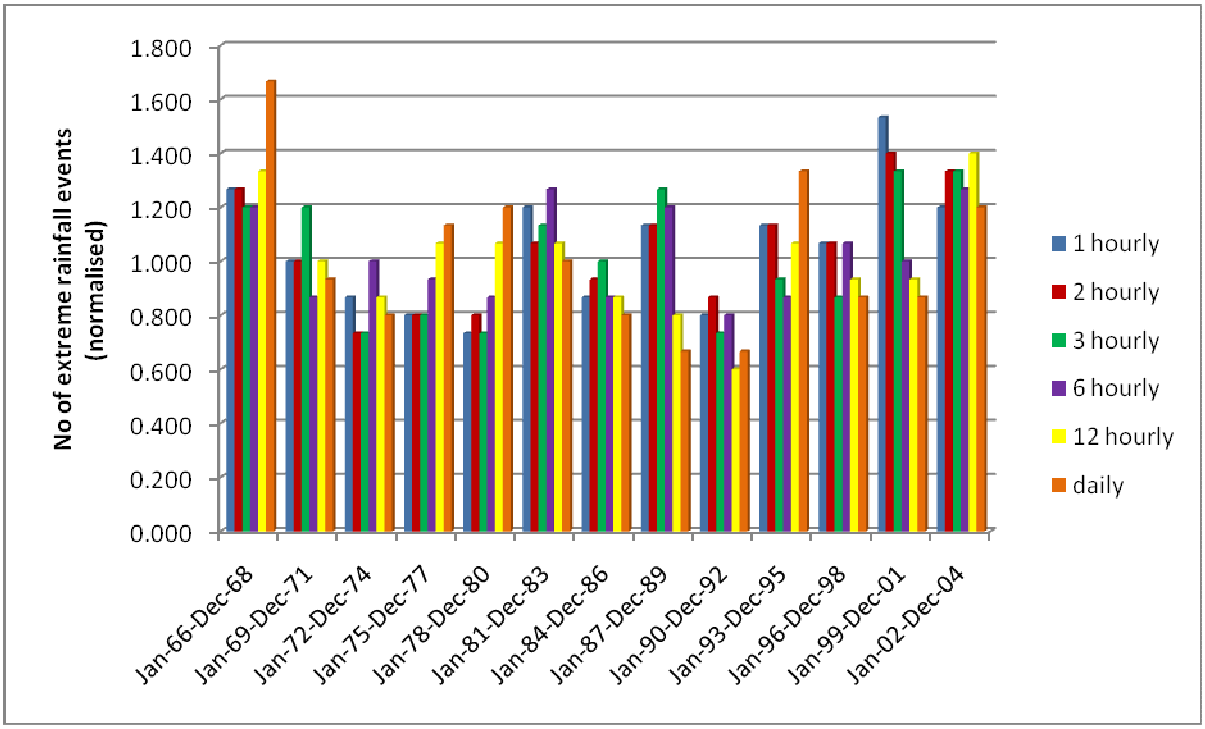


Figure 3-22 Rainfall Trend Analysis for entire catchment of Griffeen choosing different accumulation periods, 5 events per year and 3 year bins

3.2.2.1 Comment

The number of events in the winter analysis shows relatively little variation from bin to bin when compared to the similar analysis on the Owendoher catchment. A much more significant variation can be seen in the summer trend analysis, with higher numbers of events during the 1980s. However there is no apparent trend towards increased numbers of extreme rainfall events over time evident in the Casement rainfall trend analysis graphs. In a similar way the number of extreme events displayed in Figure 3-22 show a moderate variation from bin to bin compared to the Owendoher data set. While the most recent bin (2002-2004) shows an overall increase in the number of events throughout all durations, this is insufficient to conclude that there is a trend towards more rainfall events.

3.2.3 Broadmeadow at Swords (Gauge No. 08008)

The rainfall data used in the analysis of the Broadmeadow gauge records at Swords are those from the Dublin Airport Met Eireann synoptic station. A trend analysis was undertaken on the hourly rainfall depths from this station for the period 1977 to 2008 and the results are presented in Figure 3-23 to Figure 3-26. Figure 3-27 shows the results of the trend analysis for the assimilated catchment wide rainfall data of various durations based on the entire available rainfall data set.

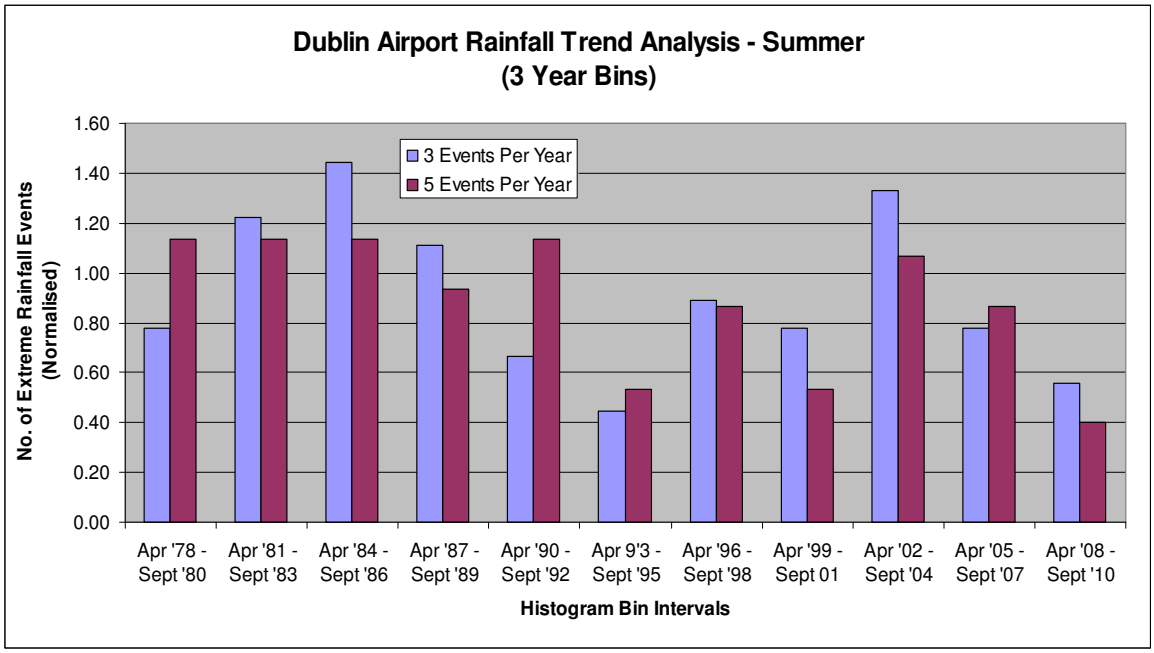


Figure 3-23 Dublin Airport Rainfall Trend Analysis – Summer (3 Year Bins)

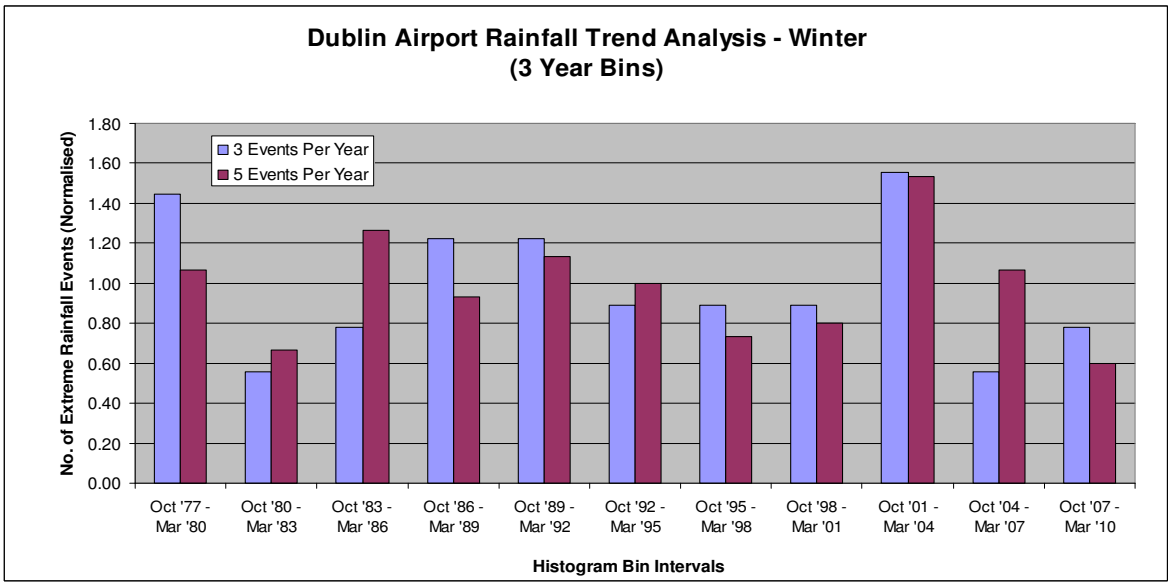


Figure 3-24 Dublin Airport Rainfall Trend Analysis – Winter (3 Year Bins)

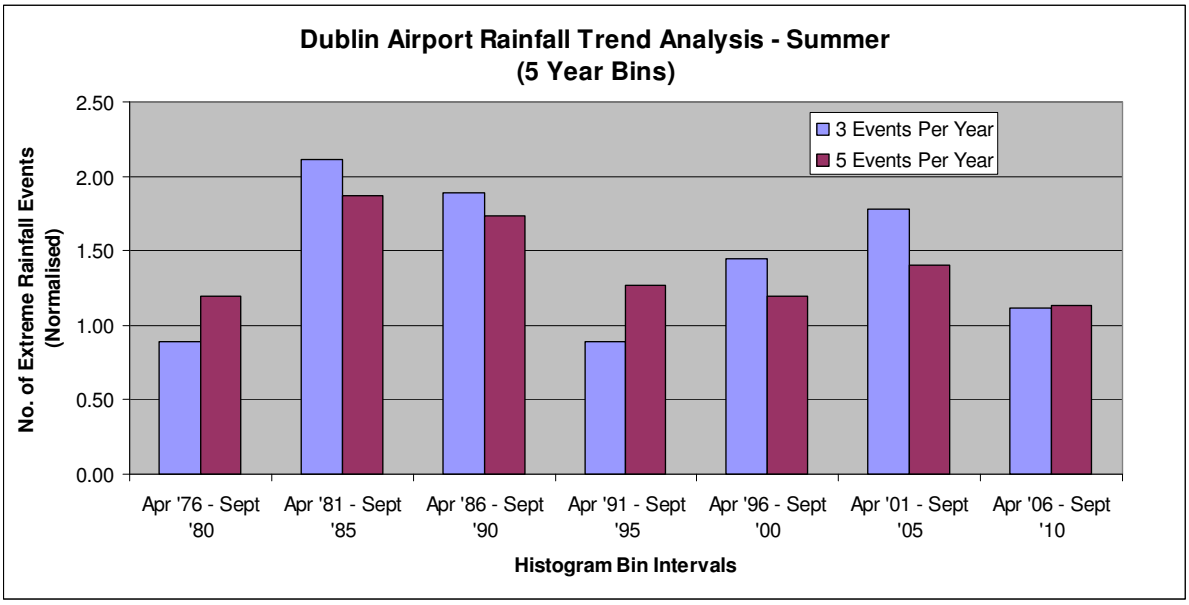


Figure 3-25 Dublin Airport Rainfall Trend Analysis – Summer (5 Year Bins)

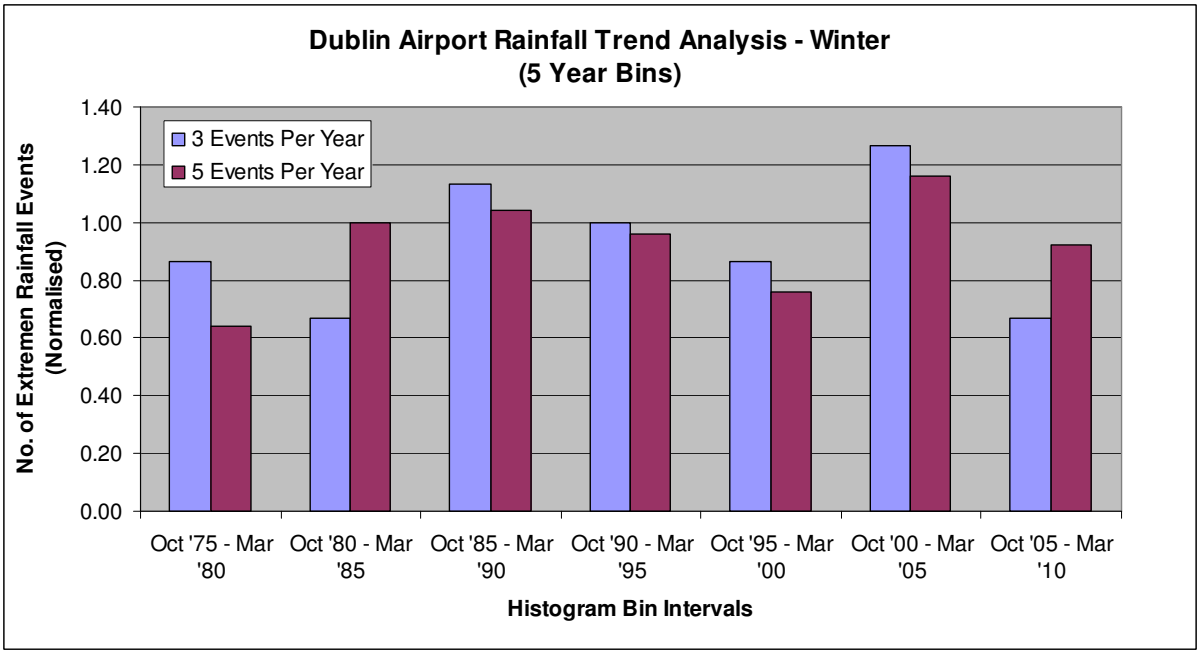


Figure 3-26 Dublin Airport Rainfall Trend Analysis – Winter (5 Year Bins)

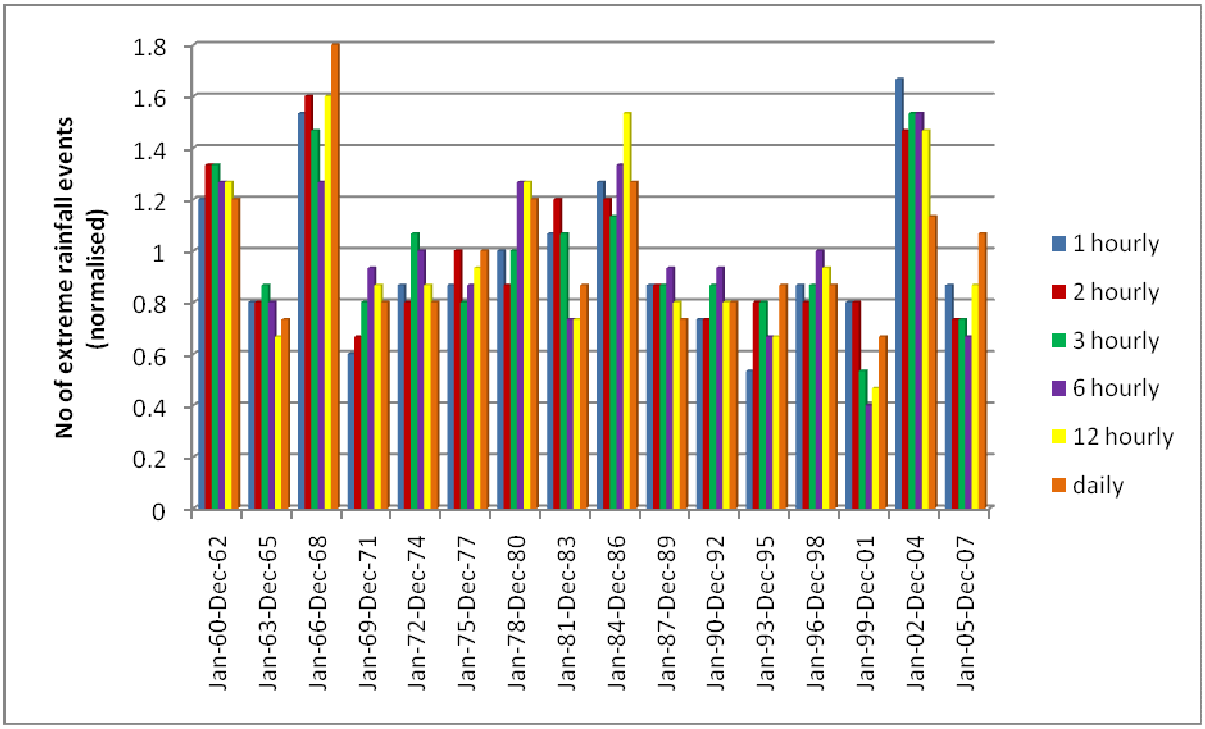


Figure 3-27 Rainfall Trend Analysis for entire catchment of Broadmeadow choosing different accumulation periods, 5 events per year and 3 year bins

3.2.3.1 Comment

The number of recorded events for the different seasonal analyses shows a slightly larger variation than was apparent in the comparable Griffeen data set, though overall it is similar to the Owendoher in this respect. From examination of the Dublin Airport rainfall trend analysis graphs it is concluded that there is no apparent trend towards increased numbers of extreme rainfall events over time. The analysis for different rainfall durations shows a couple of bins with significantly increased numbers of events spread through the analysis period. However there is no discernable trend towards increasing numbers of significant rainfall events over time.

3.2.4 Summary

The results of this analysis show that there are no obvious trends towards increased frequency of extreme rainfall events in the gauged rainfall data-sets for any of the three gauge catchments over the time period considered in this study. Therefore any trends identified in gauged discharge are unlikely to be attributable to changes in catchment rainfall over the assessment period.

3.3 CROSS-CORRELATION OF GAUGED DISCHARGE AND RAINFALL RECORDS

An analysis was undertaken to compare the number of extreme discharge events from the Griffeen gauge catchment with the number of extreme rainfall events from Casement Aerodrome for given periods of time. The purpose of this analysis was to identify any correlation between the numbers of extreme rainfall and flood events which may indicate inter-dependence between rainfall and runoff as shown in Figure 3-28 and Figure 3-29. These figures have been prepared using the discharge and rainfall trend analysis data from Section 3.1.2 and Section 3.2.2.

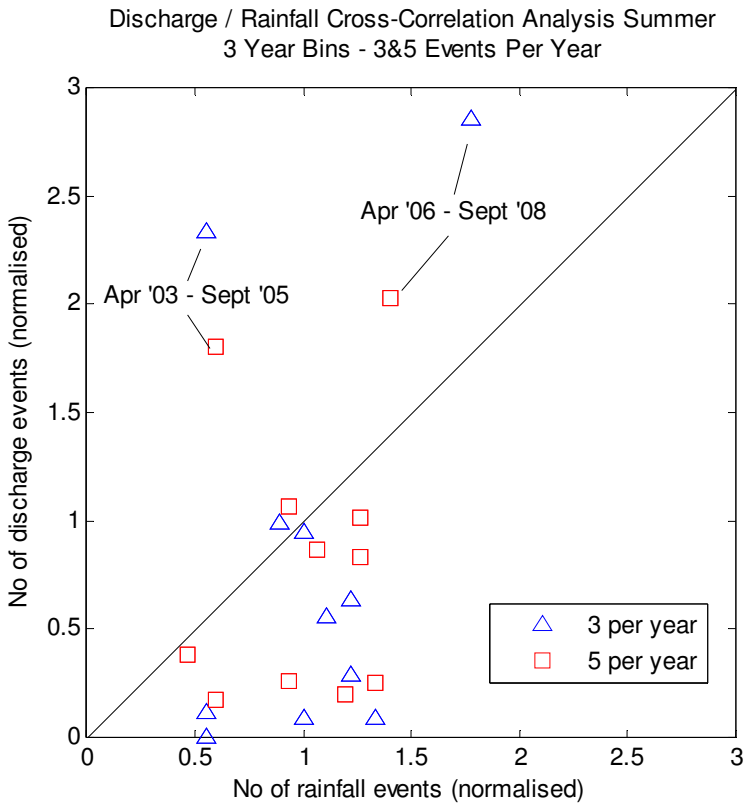


Figure 3-28 Rainfall / Discharge Cross-Correlation Analysis – Summer

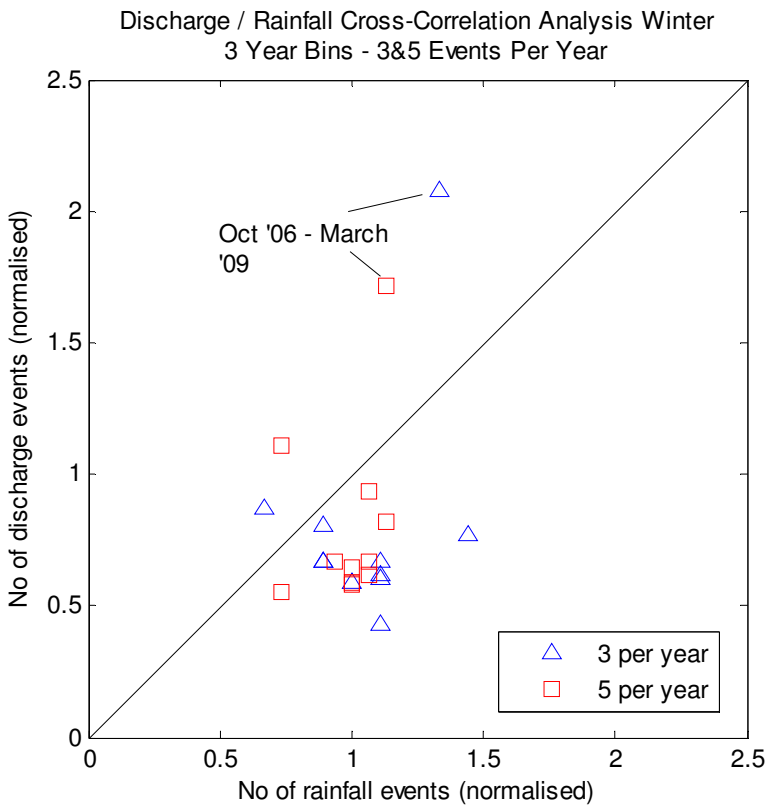


Figure 3-29 Rainfall / Discharge Cross-Correlation Analysis – Winter

3.3.1.1 Comment

The significant data scatter in the cross-correlation graphs for the summer periods (Figure 3-28) indicates a wide variation in the relationship between the numbers of extreme rainfall and discharge events. This agrees with the findings in Section 3.1.2, that there is variation in the number of extreme summer discharge events.

The clustered data pattern in the winter cross-correlation graphs (Figure 3-29) indicates that the relationship between numbers of extreme rainfall and discharge events does not vary much in the data set. This agrees with the findings in Section 3.1.2, that there is no discernable trend in the number of extreme winter discharge events.

3.4 TESTING FOR TREND THROUGH CUMULATIVE ANALYSIS

The analysis undertaken in the previous section has relied on visual inspection to determine if a trend or pattern exists. Unfortunately this can be somewhat subjective, thus another graphical analysis technique was applied. This relies on a cumulative analysis of the data and is often used in hydrology to identify changes in total or seasonal runoff. The analysis presented in this section was completed using the number of events rather the actual discharge values of the individual events. The number of events was simply added up with increasing time, thus giving the total number of extracted events as the last value. If the distribution has no change in the number of events with time, the data set should give a straight line. If the number of events decreases with time the curve should flatten, inversely if the number of events increases with time the curve should become steeper. It should be noted that the data sets used in this analysis were corrected for gaps, thus the timescale on the horizontal axis is not continuous. In addition, the way this method has been used does not account for any trend in other controlling factors, i.e. trend in rainfall intensity, evaporation, thus catchment wetness or conveyance capacity. The outcome of this analysis is presented and discussed in the following sections.

3.4.1 Cumulative trend analysis for Owendoher

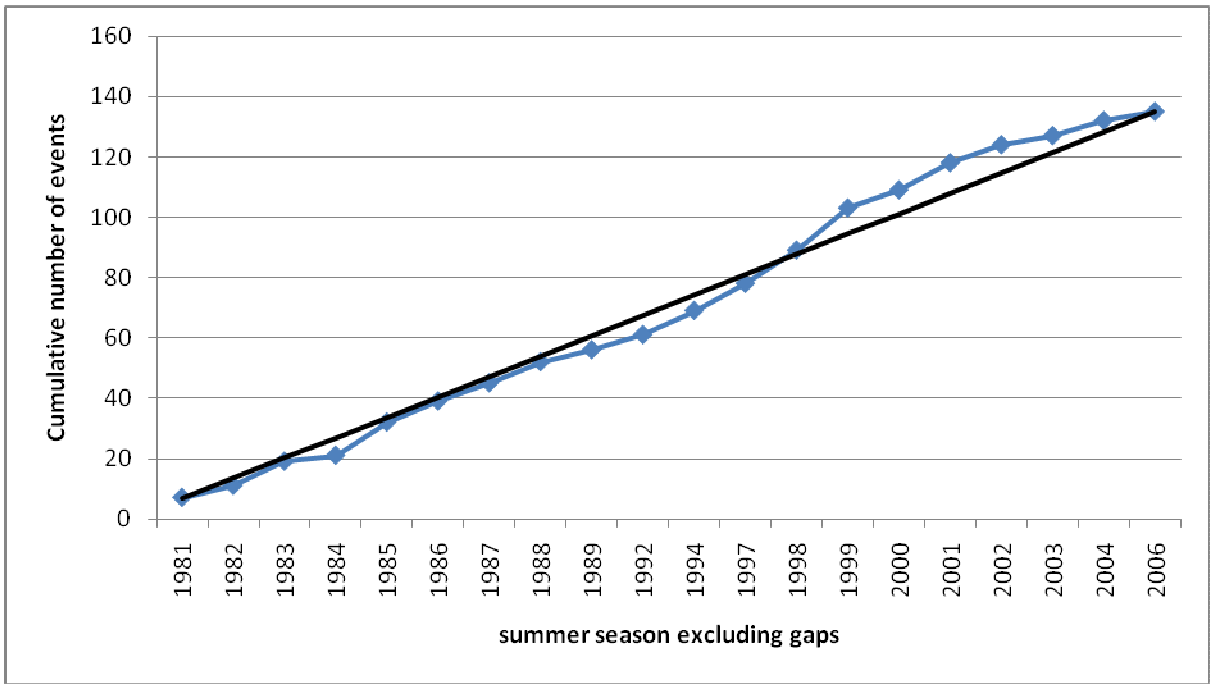


Figure 3-30 Cumulative number of events – Summer

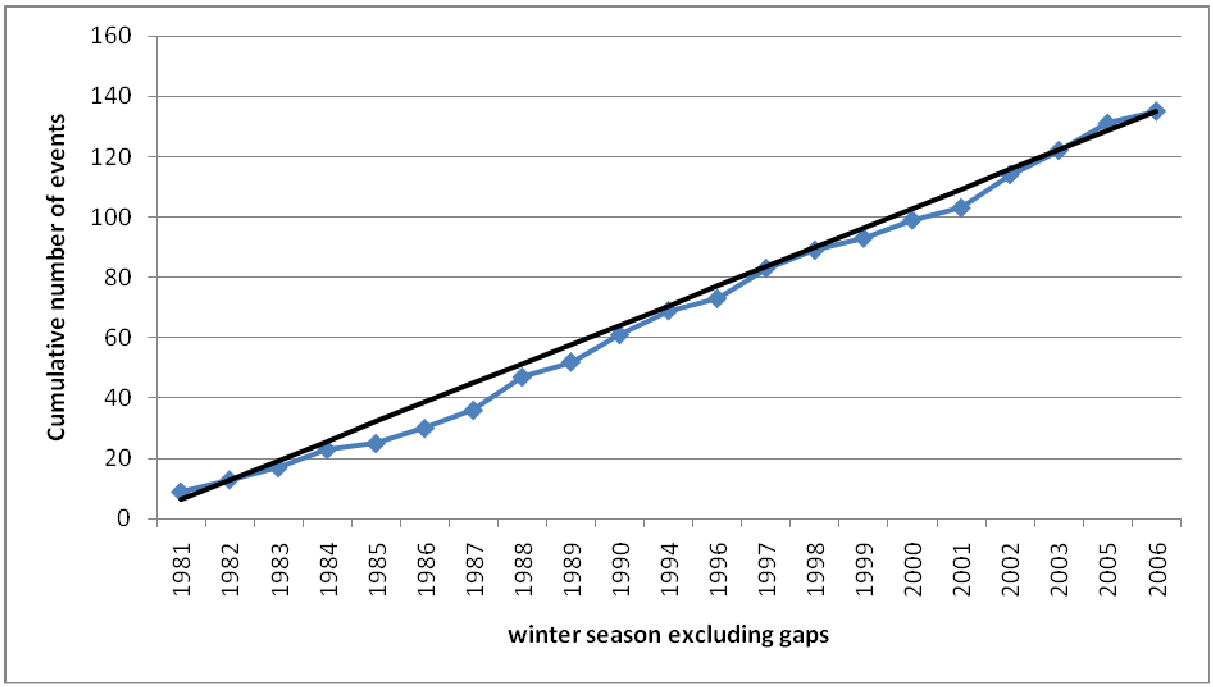


Figure 3-31 Cumulative number of events – Winter

The significant gaps in the Owendoher summer and winter data sets complicated this analysis. However, it can be seen that the first section of the diagram for the summer events follows a reasonably linear trend. In contrast it is evident that the second part of the diagram has an increasing and then decreasing slope indicating an increase in the number of events from the mid 1990's and a decrease in the latter part of the observation period. For the winter events the slope is relatively constant throughout indicating little change in the number of winter events over time. From this analysis it could be concluded that the number of summer season extreme events has increased from about the mid 1990's to around the end of the millennium but has since reduced despite increasing urbanisation while the number of winter season extreme events has remained relatively constant.

3.4.2 Cumulative trend analysis for Griffeen

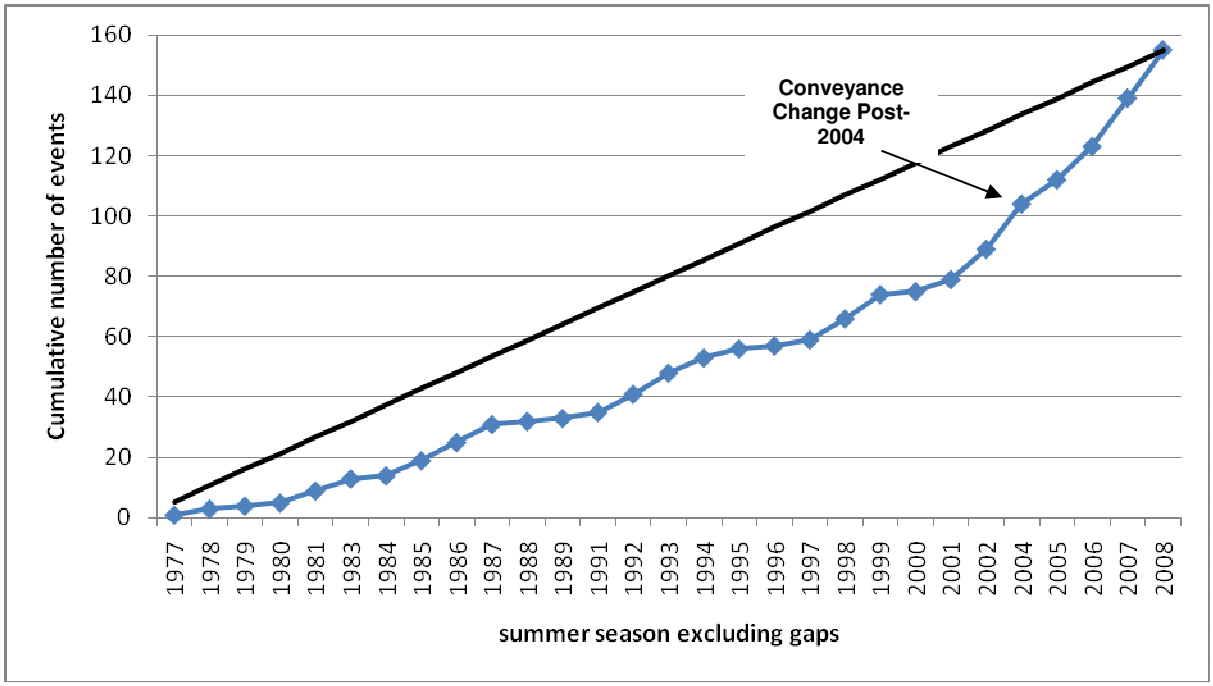


Figure 3-32 Cumulative number of events – Summer

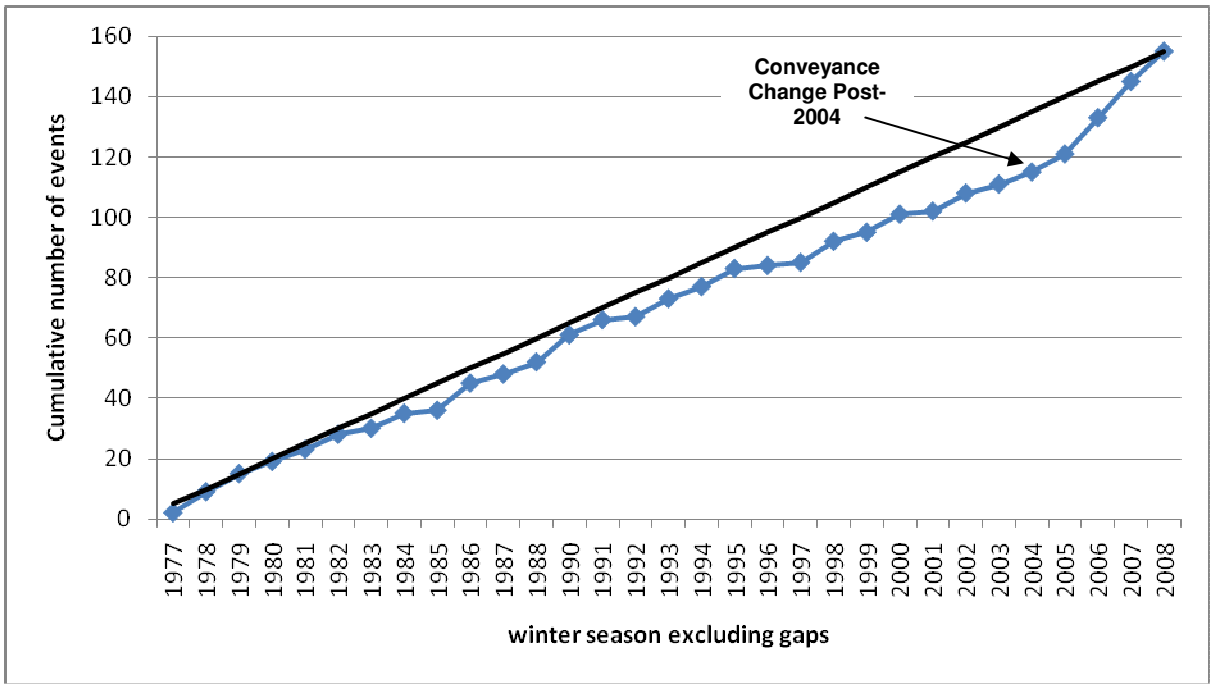


Figure 3-33 Cumulative number of events – Winter

The data gaps in this time series were relatively small and thus can probably be considered to have had a minimal impact on this analysis. Overall the diagram shows a significant trend in increasing number of events, evident through the increasing slope of the cumulative events in the summer season. For the winter season extreme events the slope seems to be relatively constant except for the last three years, where an increasing number of events can be observed. This analysis confirms that

the number of extreme events for the summer season has significantly increased throughout the observation period. In recent years the number of extreme events in the winter season has, however, also increased, which could be attributed to a change in conveyance in the lower section of the river which may be due to the flood alleviations works undertaken in the vicinity of the gauging station site circa. 2004.

3.4.3 Cumulative trend analysis for Broadmeadow

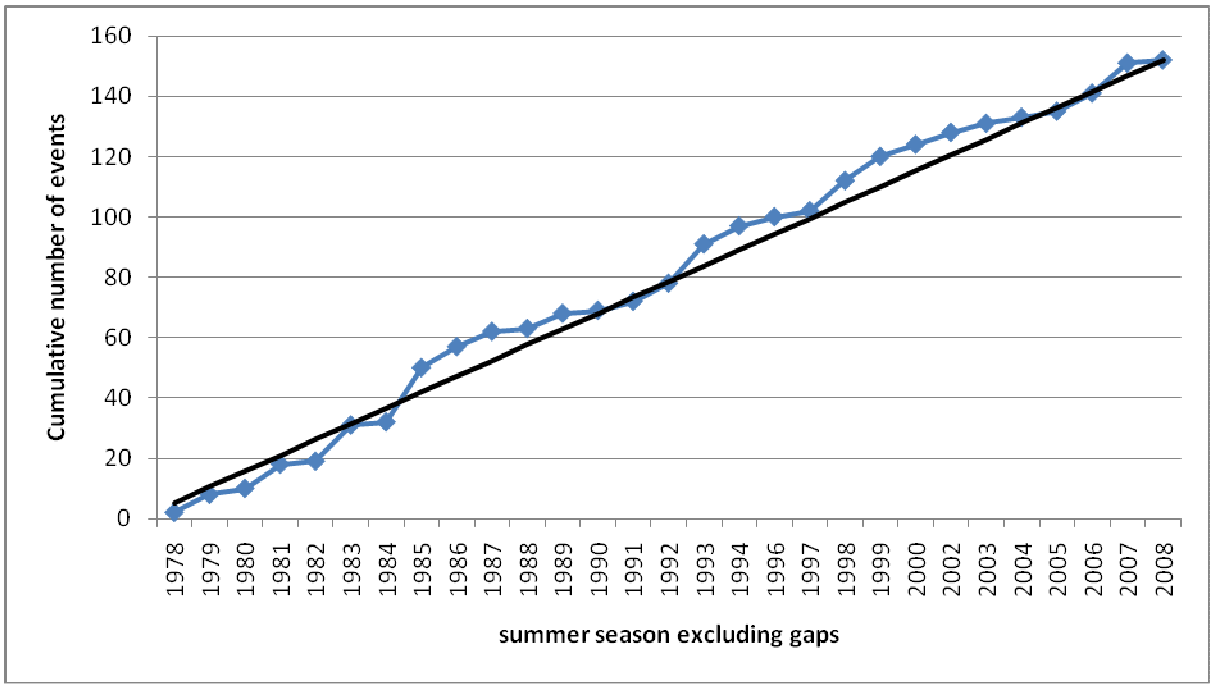


Figure 3-34 Cumulative number of events – Summer

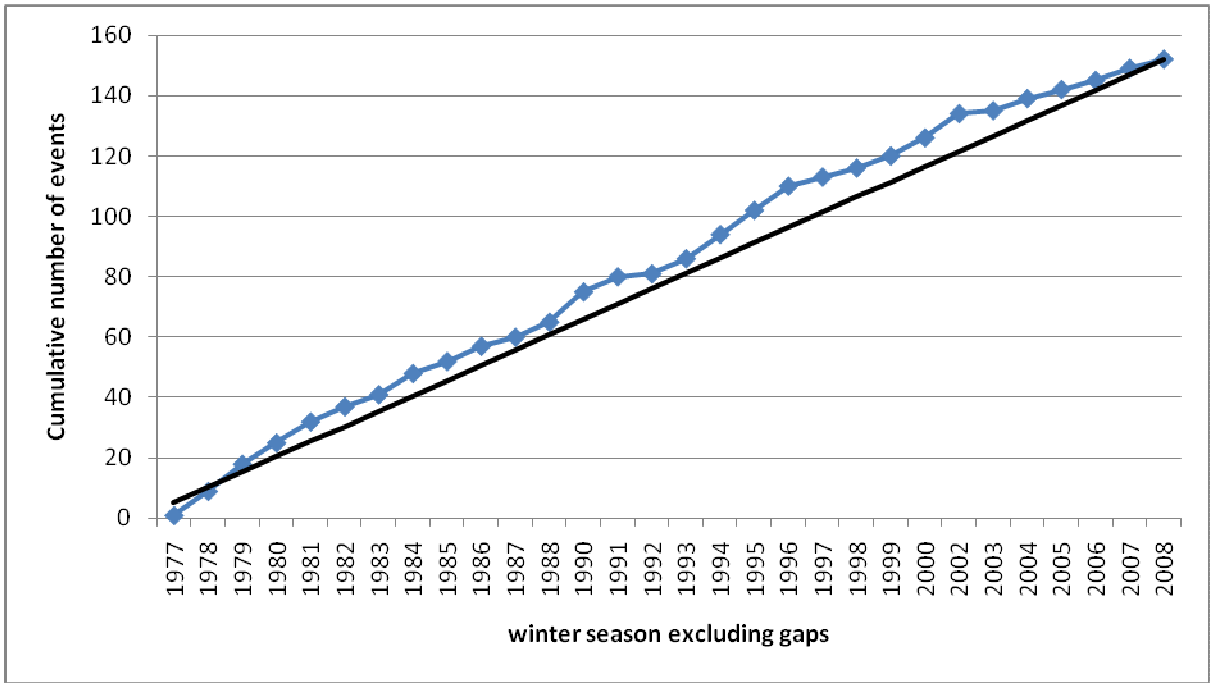


Figure 3-35 Cumulative number of events – Winter

The summer season extreme events in the above diagram show a significant variation from year to year, thus making a confident assessment slightly more difficult. A simple best fit analysis would indicate a non linear relationship with slightly decreasing slope toward the latter period of the observed data set. However this cannot be said with reasonable confidence. For the winter season extreme events the slope seems to be decreasing thus indicating a reduction in extreme runoff events. From this analysis it can be concluded that the number of extreme events overall has in fact slightly reduced despite increasing urbanisation in the Broadmeadow catchment.

3.5 TREND ANALYSIS OF GAUGED FLOW DATA USING STATISTICAL TREND ANALYSIS METHODS

The previous sections have focused on so called exploratory data analysis, using mostly graphical and visual methods to detect trends. To complement the exploratory data analysis a parallel analysis was undertaken using statistical methods for trend detection principally the Mann Kendall test. This was applied to the number of events series however there were concerns that this method was insufficient in a number of ways. In principle it can be assumed that the trend due to urbanisation would be a continuous change, thus a trend test such as Mann Kendall should be suitable. However the data gaps in some of the data sets mean that changes or trends can manifest themselves as a step variation of the mean for example in relation to the number of events. Further the Mann Kendall test is suited for linear trends only which may not be the case in terms of the effect of increased urbanisation within the study catchments. Furthermore other studies (Kundzewicz, Robson 2004) have shown that record lengths of 50 years and more are required in order to be able to truly detect trend using statistical methods, consequently this statistical approach was not pursued further for this project. Overall the results of the limited statistical analysis undertaken were not as conclusive as was initially hoped with the testing indicated that a level of statistical significance indicative of a trend with a likelihood of 1 in 20 was only found in the summer data for the Griffeen Catchment.

4 ASSESSMENT OF THE RAINFALL RUNOFF CHARACTERISTICS USING SIMULATED RUNOFF

4.1 RAINFALL-RUNOFF MODEL

Hydrological modelling for the three catchments was carried out using the Rainfall-Runoff Editor component of the MIKE 11 modelling software. Given the distinct rural and urban components of the chosen hydrometric catchments, both the NAM and the Urban models within the Rainfall-Runoff Editor were utilised.

NAM

The NAM hydrological model simulates the rainfall-runoff processes occurring at the catchment scale and can either be applied independently or used to represent one or more contributing catchments that generate lateral inflows to a river network. NAM is the abbreviation of the Danish "Nedbør-Afstrømnings-Model", meaning precipitation-runoff-model. This model was originally developed by the Department of Hydrodynamics and Water Resources at the Technical University of Copenhagen, Denmark (DHI 2009b).

The NAM rainfall runoff model is a deterministic conceptual lumped sum model, which simulates the catchment response by continuously accounting for the water storage in three interconnected reservoirs. A schematic drawing of the model is shown in Figure 4-1. The model is split into a surface storage, a lower or soil layer storage and a ground water reservoir. A key part of the modelling system is a soil moisture content module, which apportions the rainfall between ground water recharge, surface water run off, intermediate runoff and actual evapotranspiration depending on the soil moisture content. Overland flow can only occur if the surface storage is completely replenished and recharge of the groundwater body only occurs if the soil moisture is above a certain threshold. Similarly the discharge from the overland and interflow can only occur if the water content in the soil moisture model is above independently controlled thresholds.

The water discharged from the model is released through linear reservoirs with independent storage constants. Overland flow and interflow are routed through two cascaded linear storages with the time constant changing depending on the actual discharge. Thus for large flows a slightly faster discharge is achieved, which ensures that the routing of real surface flow is kinematic. The groundwater is also released with an independent time constant and can be apportioned between two reservoirs, with different discharge constants. This allows the split of the baseflow into faster and slower components and enables the simulation of, for example, the release of water from undrained bogs or groundwater bodies with different permeability. Input into the calibrated rainfall runoff simulation is in the form of time series information of total rainfall and actual evapotranspiration.

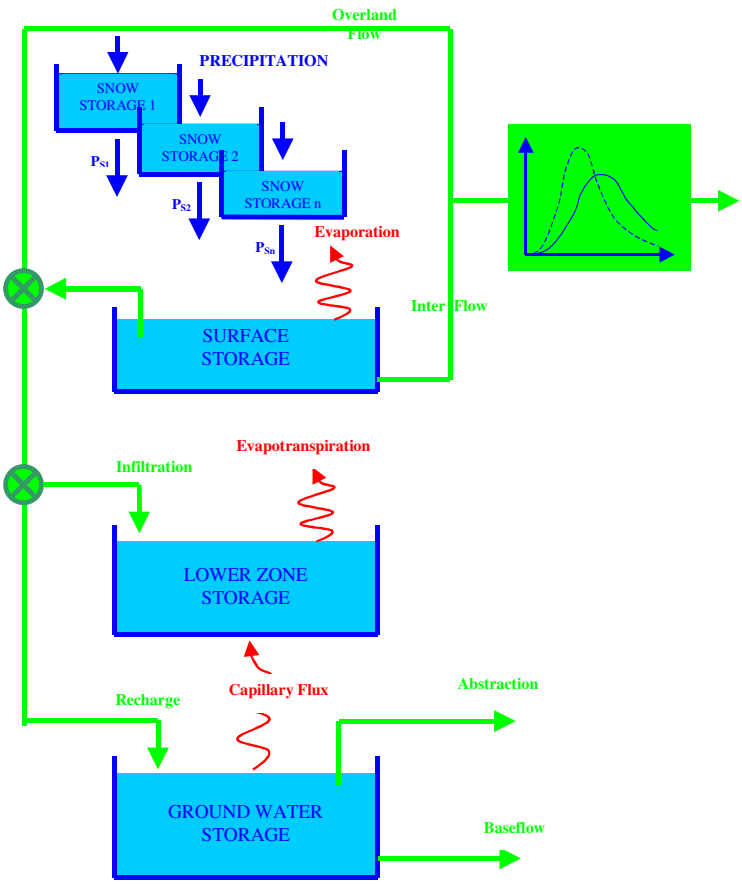


Figure 4-1 Schematic diagram of NAM rainfall run-off model

Using the basic modules of the model excluding the irrigation, abstraction and snow melt module as well as the extended ground water module there are eleven parameters available for calibration/model setup plus a further five parameters for adjusting initial conditions to suit particular start up conditions. The basic parameters are **catchment area**, four parameters for surface storage and overland runoff, three parameters for interflow and two for groundwater recharge and baseflow. In essence the model splits the discharge from the catchment into three different discharge components with different time constants for discharge, storage volumes and discharge thresholds.

The surface storage **Umax** [mm] is defined as the volume of water stored on foliage and generally on the surface following rainfall, but also in dips and puddles and subsurface non groundwater storage, which can feed the interflow discharge component. It is usually in the order of 10-20mm, is available for immediate evaporation and excludes moisture stored in soil and subsoil. Steep ground tends to have less surface storage compared to for example drumlin landscapes, also for large vegetation types i.e. trees or shrub the storage is greater compared to grass or rocky surfaces. Calibration of this parameter is often achieved through assessment of the overall water balance; this requires good evaporation information ideally varying on a weekly or monthly interval. Once the surface storage is depleted interflow ceases to exist in the model and evaporation takes place from the lower or soil moisture storage at a slower rate. Overland flow is only present while the surface storage is fully replenished in the model.

The maximum amount of overland flow is given by the overland flow runoff coefficient **CKOF** [-], which is often higher compared to other deterministic models, as the actual runoff is also proportioned in relation to the soil moisture at each time step. The soil moisture at which overland flow starts is defined by the overland runoff threshold **TOF** [-]. Overland flow and interflow together are routed through linear reservoir equations with two reservoir constants, applying Mannings formula for flows greater 0.4mm/hour. The time constants for these reservoirs **CK1,2** [hour] can be varied to control the

shape of the hydrograph, in this study they were set to the same value. The time constant can be estimated from equations such as the Kirpich formula or Time of Concentrations formulae suggested by the FSR.

Soil moisture storage **Lmax** [mm] in the model is defined as the volume of water available for access to plants and evaporation, i.e. only water in the root zone. The volume is set as the amount stored between wetting point and field capacity and is in the order of ten times the surface storage, though physically they are not necessarily linked. Moisture content above field capacity as often found in Irish catchments during wet seasons is accounted for in the surface storage, as it contributes to interflow and groundwater recharge. Calibration of the root zone storage is achieved by observing the start of discharge for overland flow at the transition from the dry to wet seasons, when the threshold of overland flow becomes less important.

The time constant for interflow **CKIF** [hour] controls how fast water can be discharged from the surface storage into the stream, though as with the overland flow this is proportioned by the ratio of available soil moisture to the total soil moisture storage. A threshold value for interflow **TIF** [-] in relation to the soil moisture content can be defined below which interflow ceases.

Recharge of the ground water reservoir is controlled by the threshold **TG** [-] and draws water in each time step from the surface storage once evaporation and overland flow have been subtracted. Recharge is again proportional to the soil moisture content in relation to the threshold value. The discharge from the ground water reservoir is simulated through a recession relationship defined by a time constant **CKBF** [hour]. As the constant already suggests the flow simulated is baseflow, i.e. a very slowly varying stream flow component, often attributed to the groundwater reservoir, though in some instances this might also be due to large peat layers in the catchments. Attempts have been made to simulate this behaviour through splitting the baseflow into two components with varying discharge time constants often found in peat catchments in wet and dry seasons.

URBAN

The Urban modelling component of the Rainfall-Runoff Module includes two modelling methods, Urban Runoff Model A (Time/Area Method) and Urban Runoff Model B (Non-linear Reservoir Method). Urban Runoff Model B has been chosen for this study as it facilitates a more detailed description of runoff surfaces in the catchments which enhances the accuracy of the hydrological models.

The basis of the surface runoff calculations of Urban Runoff Model B is the kinematic wave concept as used to solve unsteady, one-dimensional, gradually varied, open channel flow problems (DHI 2009b). In this model the runoff is calculated as flow in an open channel with only gravitational and frictional losses accounted for. The volume of the runoff is dictated by the size of the contributing catchment and hydrological losses while the shape of the runoff hydrograph is controlled by the length, slope and surface roughness of the catchment.

Urban Runoff Model B calculates the effective precipitation intensity (the precipitation which directly contributes to the surface runoff) by taking account of various hydrological losses including evaporation, wetting, infiltration and surface storage. When the effective precipitation intensity is greater than zero, runoff occurs and this is described by the kinematic wave equations for the whole surface at once. This model facilitates the description of five different surface types in one catchment, with the runoff computations for each catchment calculated individually. The runoff is defined using a kinematic runoff equation based on Mannings formula, using the catchment “width” (areas divided by drainage length) and the runoff depth calculated in each time step.

In this study the five areas are defined as impervious steep areas (roofed), flat impervious areas such as roads, car parks and paved areas, pervious areas with three different rates of infiltration such as well drained grass land, gardens and undrained “natural” parkland. From experience it has been found that maintaining a certain set of Mannings number values, wetting and storage values and values for infiltration for these five areas is sufficient and variation of the area proportions yields sufficient scope

for calibration. The standard values employed for this study are given in the table below and were not altered between the different catchments.

	Impervious areas		Pervious areas with infiltration		
	Sloped roof	Flat	small	medium	large
Mannings number [$m^{1/3}/s$]	60	40	20	15	15
Initial wetting loss [mm]	0.05	0.5	2	5	8
Storage loss [mm]		1.8	2	3	5
Infiltration start [mm]			3	6	6.6
Infiltration end [mm]			0.25	0.5	0.5
Horton exponent (wetting) [sec^{-1}]			0.0015	0.0015	0.0015
Horton exponent (drying) [sec^{-1}]			3.00E-05	3.00E-05	3.00E-05

Manning's number is here defined as M [$m^{1/3}/s$] = 1 / n.

Table 4.1 Table of Mannings number, Wetting and Storage Loss for Urban Catchment

At the start of a rainfall event the wetting losses are taken off the actual precipitation, following this storage losses are accounted for, followed by the infiltration losses. The infiltration losses are reduced with time using the Horton equation from a start value to an end infiltration under wet conditions, with the time element defined by the Horton exponent. At the end of the rainfall event an inverse Horton equation is used to derive the recovery of infiltration with time defined by the second Horton exponent. At this stage the wetting and storage losses are reset.

The parameters defined in the calibration/model setup are **catchment area**, **drainage length**, **surface slope** and **proportions of pervious and impervious areas**. The catchment areas were derived from the spatial analysis and the drainage length from the known drainage network. In the case of the Owendoher this was relatively easy to estimate, as the urban area is situated at the bottom of the catchment. In both the Griffeen and Broadmeadow catchment the urban areas are spread across the catchment and urban runoff entering the stream from the areas situated further upstream will still have to travel a substantial distance down the stream to the gauge. On the other hand it can be argued that in a combined sewer system such as those in the study area the discharge travels at relatively high speed to storm overflows at lower reaches of the stream compared to the flood wave in the river. The drainage length was therefore used as a calibration tool, initially estimated from drainage length of the longest drainage system in the catchment. The proportioning between the different impervious areas was initially derived from the aerial photography by estimation of road, roof and grass land areas. In the calibration process these were marginally changed to better reflect observed runoff patterns. In reality it has been found that rather bold variations are required to make measurable changes to the discharge in a combined (NAM& Urban) runoff system. Evaporation was not simulated as a separate controlling parameter, instead the wetting and storage losses were set to account for evaporation in the urban model.

COMBINED

Combined models were produced by joining together the NAM and Urban models for each of the chosen hydrometric gauge catchments. These combined models were calibrated against recorded flow data from the gauges and then run with gauged and current catchment characteristics to simulate appropriate runoff responses.

Combined models were produced for each of the three hydrometric gauge catchments.

Distribution and Weighting of Rainfall

The time series rainfall data from the individual stations was also included in the model. The distribution of rainfall was defined both in terms of time series and contribution to the catchment as defined by Voronoi polygons. The actual distribution of the rainfall over the catchment is detailed in the relevant data input sections of the catchment description. If the rainfall time series of an individual station did not cover the simulation period or had missing data (flagged by a 'no data' tag), the model automatically recognised this and redistributed the rainfall from the other stations accordingly to maintain the correct water balance and weighting.

RAINFALL-RUNOFF MODEL CALIBRATION

The combined rainfall-runoff models for the three gauge catchments were calibrated against recorded discharge files. The calibration process involved adjusting the various NAM and Urban model parameters to appropriately reflect the catchment characteristics and attempt to match the modelled discharge file to the recorded data. Recently recorded rainfall data (recorded within the past eight years) was used in the calibration process to create the simulated discharge files.

The objectives of the model calibration were to have good match between:

1. Simulated and observed catchment runoff (i.e. a good water balance);
2. Simulated and observed hydrograph shapes;
3. Simulated and observed peak flows with respect to timing, rate and volume;
4. Simulated and observed low flows.

To assess the quality of the model calibration the RR module in Mike 11 provides two parameters which compare the modelled discharge data with observed or recorded discharge data. The parameters are as follows:

A. **Overall Water Balance Error**: The difference between the average simulated and observed runoff. This is expressed as a percentage.

B. **Overall Shape of Hydrograph (R^2)**: A measure of the overall shape of the hydrograph based on the Nash-Sutcliffe coefficient. A perfect match corresponds to $R^2 = 1$

$$R^2 = 1 - \frac{\sum_{i=1}^{N} [Q_{obs,i} - Q_{sim,i}]^2}{\sum_{i=1}^{N} [Q_{obs,i} - \overline{Q}_{obs}]^2}$$

Where
$Q_{sim,i}$ = simulated discharge at time i
$Q_{obs,i}$ = corresponding observed discharge
Q_{obs} = average observed discharge

Equation 4-1 Nash Sutcliffe Coefficient

4.2 OWENDOHER AT WILLBROOK ROAD (GAUGE NO. 09009)

The rainfall-runoff model for the Willbrook Road hydrometric catchment was created for the River Dodder CFRAMS.

4.2.1 Data Input

Recorded rainfall data from a number of rain gauges within or adjacent to the Willbrook Road gauge catchment were entered into the rainfall runoff model and weighted according to their contribution relative to the catchment area using Voronoi polygons. Table 4.2 presents details of the contribution of individual rainfall gauge data to the overall gauge catchment and gauge data record lengths.

	Willbrook Road	
Rainfall Gauge Stations	**Contribution (%)**	**Rainfall Gauge Record**
Glenasmole (Castlekelly)	6.9	1959 - 2007
Glenasmole (Supt.'s Lodge)	0.9	1959 – 2006
Knocklyon (St. Colmcille's)	2.7	2004 – 2005
Ballyboden	20.9	1966 - 2007
Rathfarnham (St. Columba's)	13.1	1972 – 1995
Tibradden (Larch Hill)	54.4	1967 – 1990
Ballyedmonduff House	1.0	1985 - 2007
Total	100	-

Table 4.2 Rainfall Gauge Data for Willbrook Road Gauge Catchment

The rainfall data from Table 4.2 was temporally distributed according to the rainfall pattern from the hourly rainfall data recorded at Casement Aerodrome. The resulting rainfall file spans the available data record length of the combined rainfall gauging stations. Evapotranspiration data from 1964 to 2007 for the Casement Aerodrome synoptic station was also entered into the model to provide an accurate picture of hydrological conditions in the catchment.

NAM parameters prepared as part of a study undertaken for the Water Framework Directive (WFD) Project were used in the River Dodder CFRAMS rainfall-runoff model for the Willbrook Road gauge catchment. The WFD Project provides NAM parameters based on catchment characteristics using various GIS layers. Table 4.3 presents the NAM parameters provided by the WFD study for the Willbrook Road gauge catchment.

	NAM Parameters			
Water Level Gauge Catchment	**CQOF**	**UMAX**	**CKIF**	**CKBF**
Willbrook Road Gauge Catchment	0.90	15 - 20	~ 200	2892.80

Table 4.3 NAM Parameters Supplied by Water Framework Directive Project

4.2.2 Calibration

The rainfall-runoff model for the Willbrook Road gauge catchment was calibrated against recorded flow data from 01/05/2002 to 31/12/2006. Figure 4-2 presents the simulated and observed discharge files for Willbrook Road gauge catchment following the calibration process.

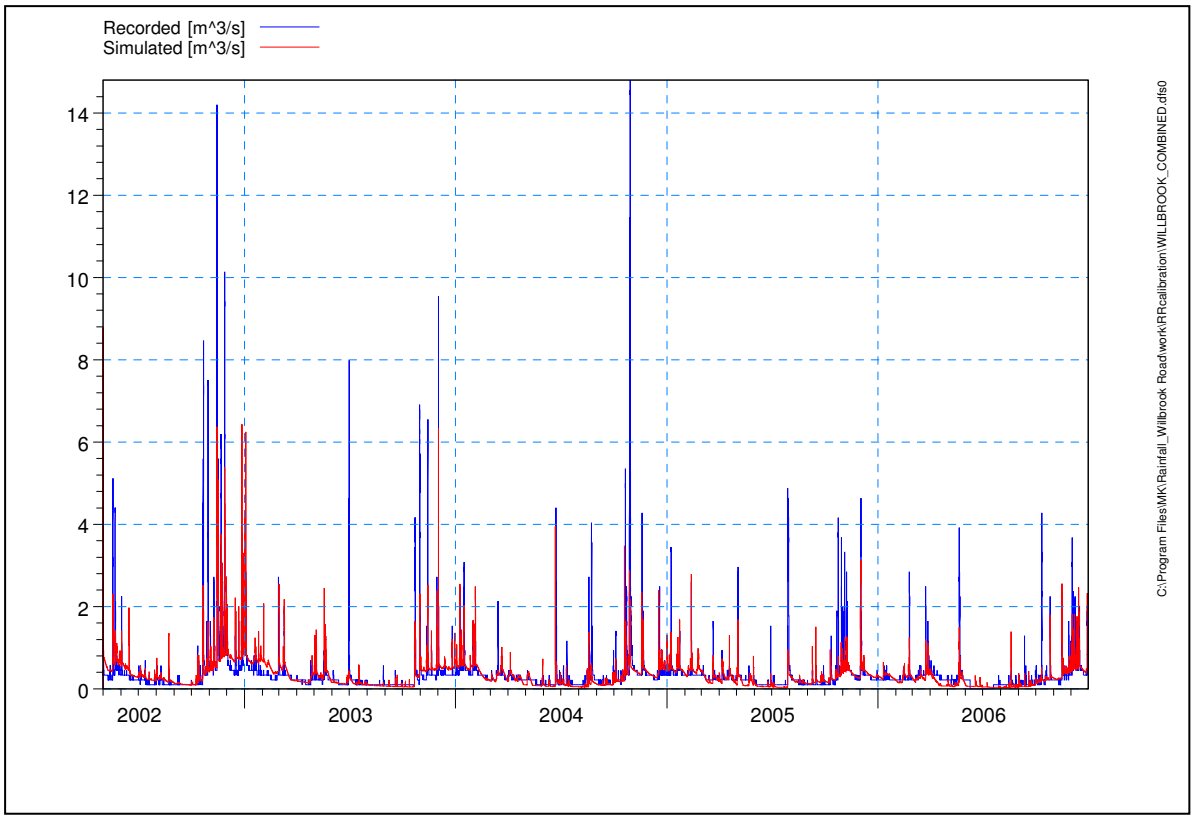


Figure 4-2 Simulated V Recorded Discharge for Willbrook Road Gauge Catchment

From examination of the simulated and recorded discharge data it can be seen that the simulated discharge peaks do not coincide with the peaks in the observed record. However the simulated low flow data compares well with the observed data. Detailed examination of the model inputs and outputs indicates that the difficulty in calibrating peak discharges is primarily due to the inaccuracy of the rainfall data input. For example Figure 4-3 and Figure 4-4 present the recorded rainfall and recorded discharge for a sample event from the Willbrook Road gauge catchment calibration period. From these figures it can be seen that the rainfall does not accurately match the discharge. For example in early October 2005 there is a significant rainfall event with recorded rainfall depths up to 8.5mm which coincides with a maximum recorded discharge of 1.3m^3/s. Then around the 20th October there is a recorded rainfall event with a maximum depth of 3.6mm which coincides with a recorded discharge of 1.8m^3/s. These two events had similar antecedent conditions.

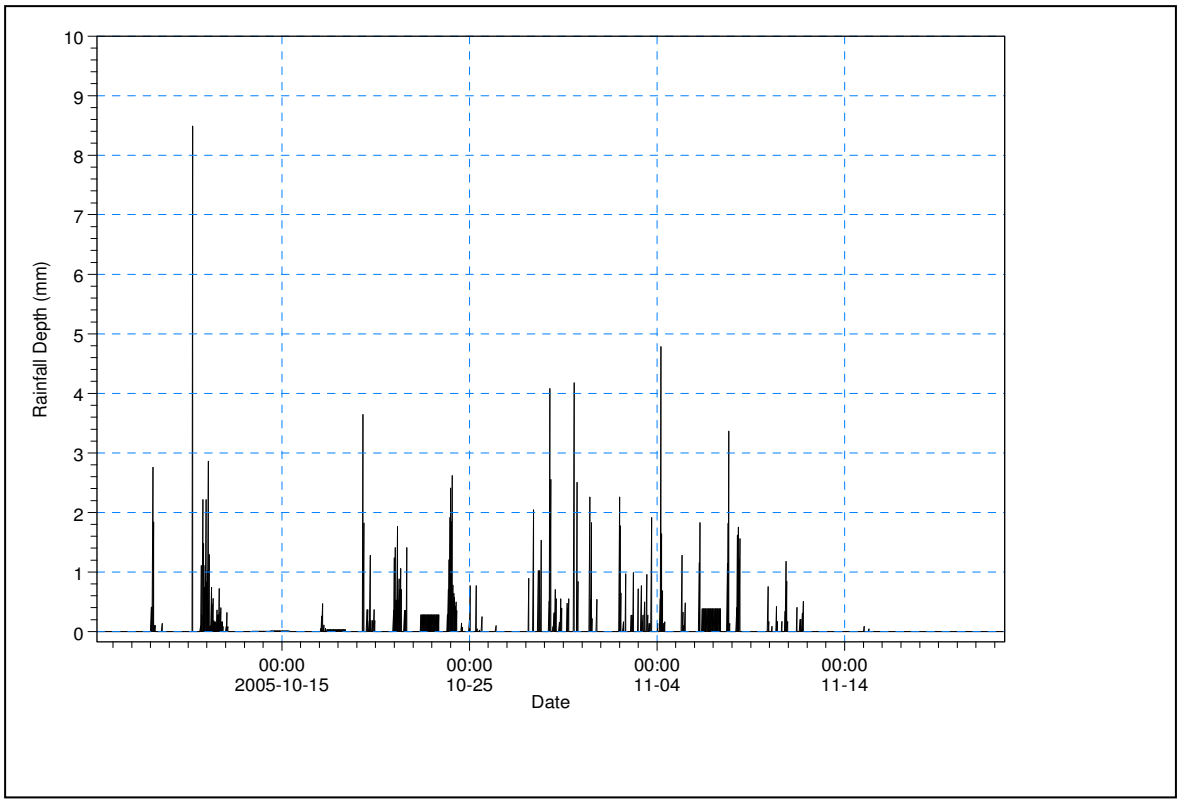


Figure 4-3 Recorded Rainfall for Sample Event

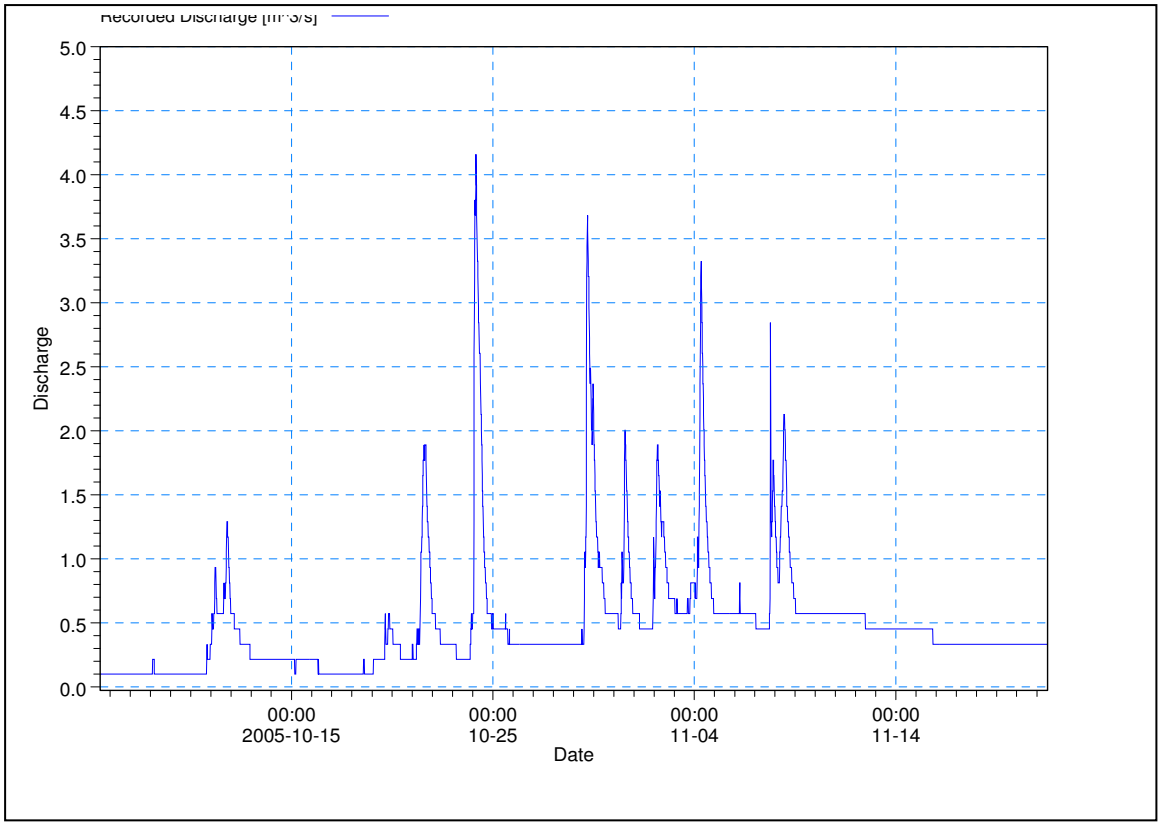


Figure 4-4 Recorded Discharge for Sample Event

From Table 4.2 it can be seen that only Glenasmole (Castlekelly), Glenasmole (Supt's Lodge), Ballyedmonduff House and Knocklyon (St. Colmcille's) rainfall gauges were recording during the chosen calibration period. Of these four gauges, three are located above 180mOD which gives a bias towards mountainous rainfall patterns and therefore does not necessarily accurately represent the rainfall characteristics of the whole catchment. The observed discharge records indicate that peak discharges are occurring at the time of recorded rainfall events, but they do not directly match each other in terms of time or intensity. It was therefore concluded that the coverage of rainfall data used in the calibration process was not sufficient to accurately reproduce the observed discharge record.

The Nash Sutcliffe coefficient R^2 in this calibration was below 0.7 which is considered in general as a poor correlation. Despite various attempts to improve the correlation, this proved to be unsuccessful, which is most likely attributable to the mismatch in recorded events and rainfall as explained above. In order to provide an alternative assessment of the correlation between the model and actual catchment a number of statistical parameters were obtained from the calibration period based on a peak over threshold analysis for 5 events per year. These are the average of the event magnitudes, the median of all events extracted and the standard deviation. These are compared in terms of observed and simulated events in the table below.

	Simulated	Observed
Average	6.09	6.98
Median	5.57	5.78
Standard deviation	1.71	3.26

Table 4.4 Comparison of extreme event statistics derived from POT of calibration period

As stated earlier the match is not particularly good, though both average and median only differ by 13% and 4% respectively, whereas the variation is far larger in the observed events than in the model output. It can however be seen, that on average the events are of similar magnitude and that the 50 percentile is very close to the observed data.

Thus it was concluded that the rainfall-runoff model for the Willbrook Road gauge catchment was producing simulated discharge data which is similar to the observed data in terms of frequency of discharge peaks. However the magnitude of the peaks differs to a significant degree. The NAM parameters used in the RR model were derived as part of a Water Framework Directive project and are judged to be accurate and the Urban parameters are taken directly from the catchment characteristics. Thus difficulties with the calibration exercise are attributed principally to inaccurate coverage of recorded rainfall data.

4.2.3 Simulated Discharge Data

Using the calibrated rainfall runoff model, discharge data was generated for different urban percentages by varying the size of the urban extent in the Willbrook Road gauge catchment model. The indicated size of the urban extent relates to catchment urbanisation for specific years (1973, 1995, 2000 and 2008) and was taken from Table 2.1 in Section 2, reproduced here as Table 4.5.

Year	Area	Percentage of Total Catchment Area
	(km^2)	(%)
1973	0.85	3.7
1995	3.17	14.0
2000	3.29	14.5
2008	3.39	14.9

Table 4.5 Willbrook Road Gauge Catchment Urban Data

The simulated flow data for each of the urban extent data sets are presented in Figure 4-5.

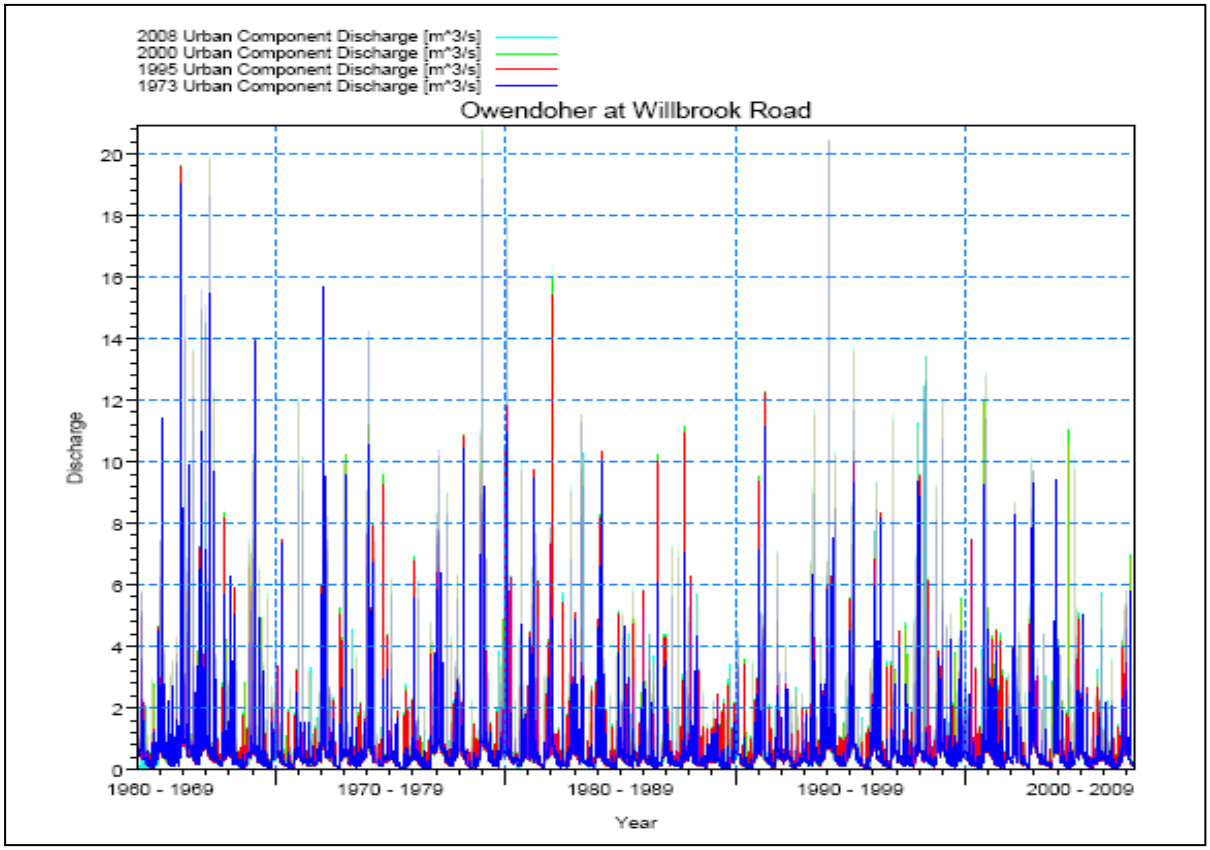


Figure 4-5 Simulated Discharge with Varying Urban Extent for Owendoher at Willbrook Road

4.3 GRIFFEEN AT LUCAN (GAUGE NO. 09002)

4.3.1 Data Input

Recorded rainfall data from a number of rain gauges within or adjacent to the Griffeen gauge catchment were entered into the rainfall runoff model and weighted according to their contribution relative to the catchment area using Voronoi polygons. Table 4.6 presents details of the contribution of each rainfall gauge data to the overall gauge catchment and the individual gauge data record lengths.

	Griffeen at Lucan	
Rainfall Gauge Stations	**Contribution (%)**	**Rainfall Gauge Record**
Casement Aerodrome	37.5	1969 - 2008
Rathcoole	37.5	1969 - 2001
Leixlip (Gen. St.)	15	1949 - 2006
Brittas (Glenarneen)	10	1975 – 2006
Total	100%	-

Table 4.6 Rainfall Gauge Data for Griffeen Gauge Catchment

The rainfall data from the stations listed in Table 4.6 was temporally distributed according to the rainfall pattern from the hourly rainfall data recorded at Casement Aerodrome. The resulting rainfall file

spans the combined data record length of the rainfall gauging stations. Evapotranspiration data from 1941 to 2008 for the Casement Aerodrome synoptic station was also entered into the model to provide an accurate picture of hydrological conditions in the catchment.

NAM parameters were estimated based on modelling experience and manually adjusted in the calibration process to improve the fit to the observed discharge.

4.3.2 Calibration

The rainfall-runoff model prepared for the Griffeen gauge catchment was calibrated against recorded flow data from 12/02/2004 to 03/12/2008. Figure 4-6 presents the simulated and observed discharge files for this gauge catchment following the calibration process.

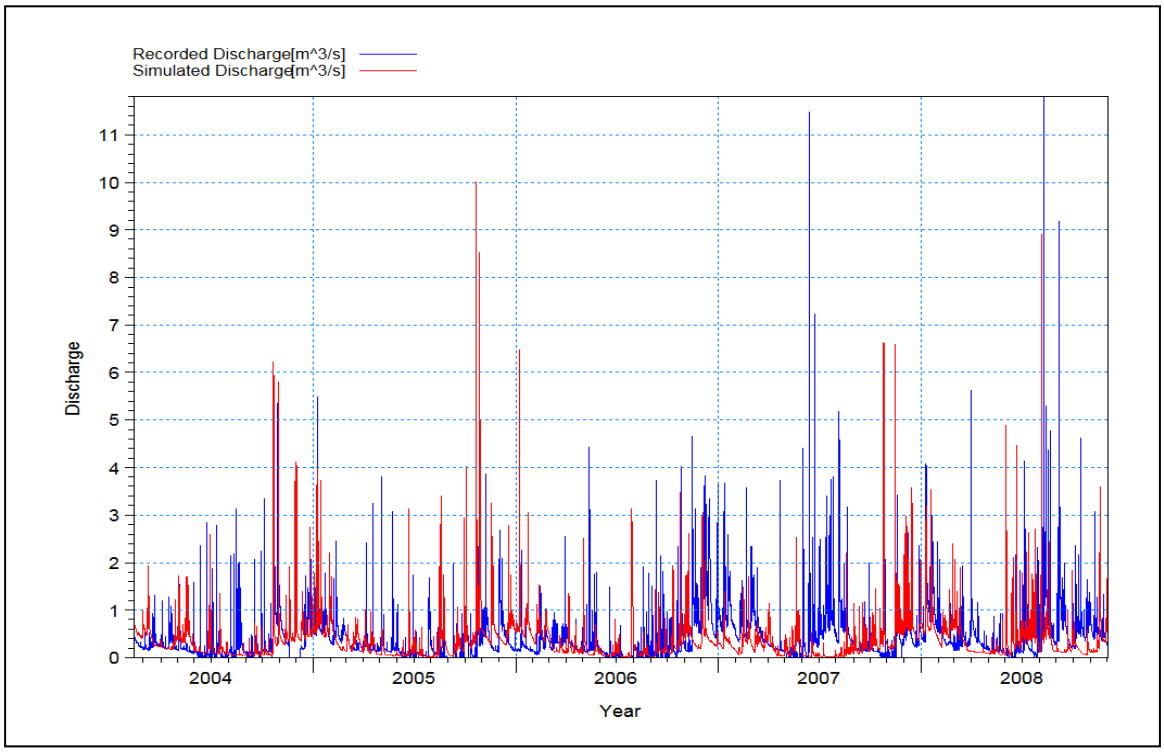


Figure 4-6 Recorded V Simulated Discharge for Griffeen Gauge Catchment

The overall calibration parameter obtained from the calibration process was as follows:

R2: 0.786

A coefficient of this value indicates that there is an acceptable correlation between recorded and simulated discharge data, although values of 0.8 or higher are desirable. As in the previous section the basic statistical values for the extreme events based on a 5 per year data set are shown in the following table.

	Simulated	Observed
Average	6.18	5.52
Median	4.83	4.65
Standard deviation	3.02	2.25

Table 4.7 Comparison of extreme event statistics derived from POT of calibration period

In this instance the magnitude of the extreme events are slightly overestimated in the simulated data set compared to the observed values, though the variation is closer when compared to the previous catchment.

The differences between the observed and simulated discharge data are attributed to inaccuracies in the spatial and temporal distribution of rainfall data within the Griffeen gauge catchment. Three out of the four rainfall gauges listed in Table 4.6 only record daily rainfall totals. The hourly temporal rainfall pattern was therefore taken from the rainfall recorded at the synoptic station at Casement Aerodrome. For this reason the intensity of rainfall events localised to the Griffeen gauge may not be accurately represented by the temporal distribution derived from the Casement Aerodrome gauge. However, the overall distribution of events between observed and simulated discharges were very similar and it was therefore accepted that the model was accurately representing the relationship between rainfall and runoff in the catchment.

4.3.3 Simulated Discharge Data

Using the calibrated rainfall runoff model, discharge data was generated for different degrees of urbanisation by varying the size of the urban extent within the Griffeen gauge catchment model. The size of the urban extent relates to catchment urbanisation for specific years (1973, 1995, 2000 and 2008) and was taken from Table 2.1 in Section 2, reproduced here as Table 4.8**.**

Year	Area	Percentage of Total Catchment Area
	(km^2)	(%)
1973	1.95	5.6
1995	4.04	11.6
2000	6.23	17.9
2008	8.55	24.6

Table 4.8 Griffeen at Lucan Gauge Catchment Urban Data

The simulated flow data for each of the urban extents are presented in Figure 4-7.

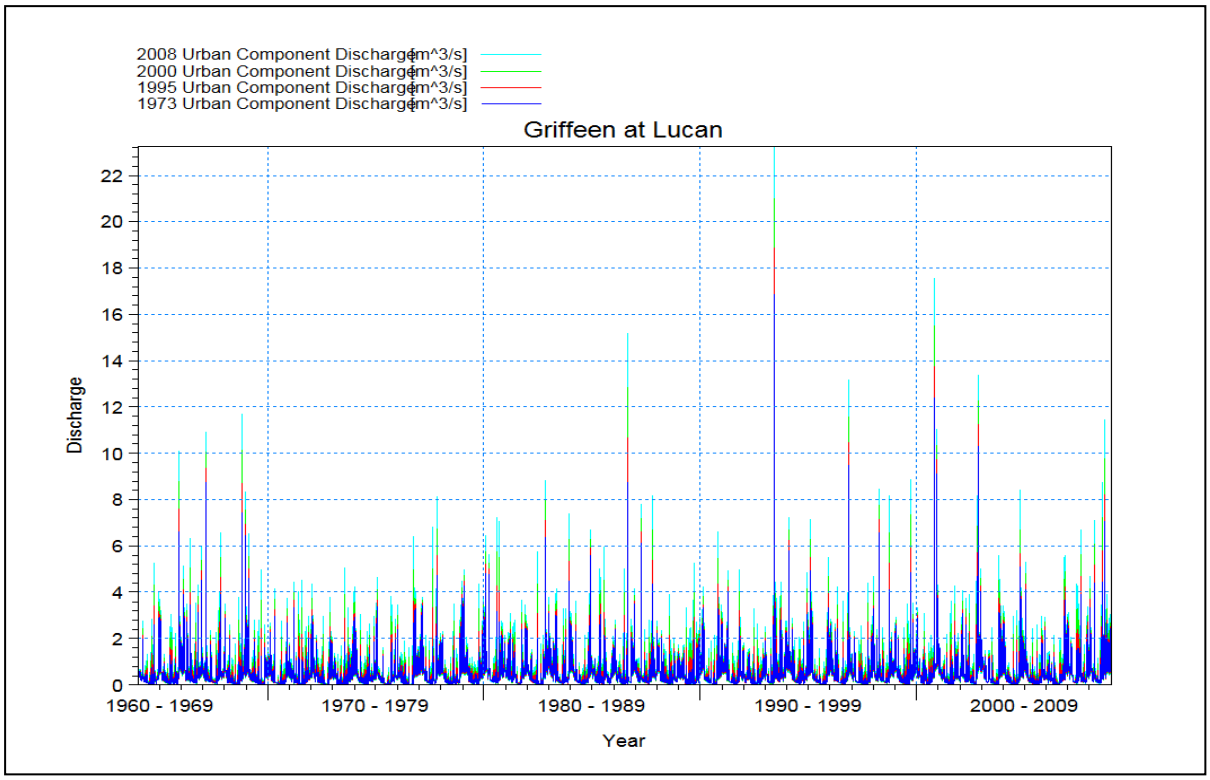


Figure 4-7 Simulated Discharge with Varying Urban Extent for Griffeen at Lucan

It can be seen from Figure 4-7 that the peak flows for the different urban extents gradually increase from 1973 to 2008. This coincides with an increase in the extent of urbanisation within the catchment from 1973 to 2008.

4.4 BROADMEADOW AT SWORDS (GAUGE NO. 08008)

4.4.1 Data Input

Due to the proximity of the Dublin Airport Synoptic station to the Broadmeadow gauge catchment, the hourly rainfall depths and temporal distribution from this station for 1960 to 2009 were used as inputs to the Broadmeadow River rainfall-runoff model. Evapotranspiration data from 1941 to 2008 for Dublin Airport synoptic station was also entered into the model to provide an accurate picture of hydrological conditions in the catchment.

NAM parameters were estimated based on modelling experience and manually adjusted during the calibration process.

4.4.2 Calibration

The rainfall-runoff model prepared for the Broadmeadow gauge catchment was calibrated against recorded flow data from 24/05/2005 to 19/05/2008. Figure 4-8 presents the simulated and observed discharges for this gauge catchment following the calibration process.

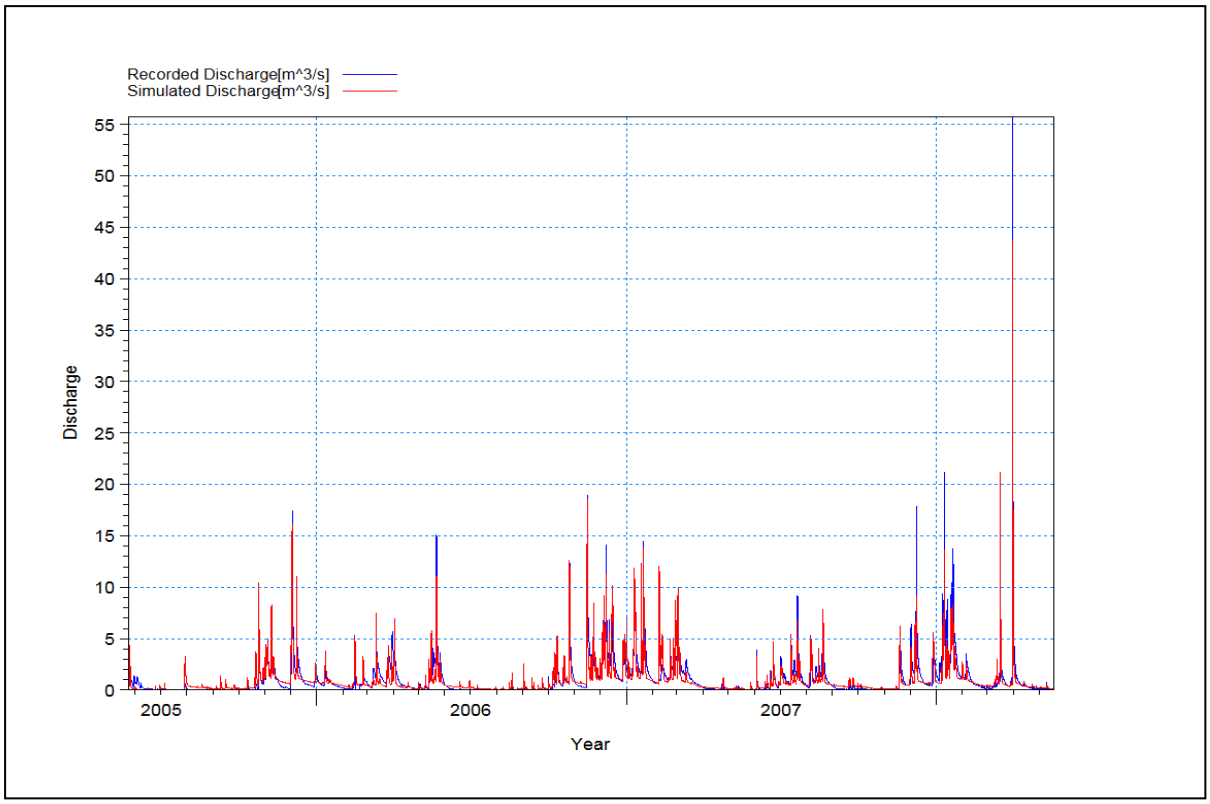


Figure 4-8 Recorded V Simulated Discharge for Broadmeadow Gauge Catchment

The overall calibration parameter obtained from the calibration process was as follows:

R2: 0.730

A coefficient of this value indicates that there is a poor correlation between recorded and simulated discharge data, as it is less than 0.75. As in the previous section the basic statistical values for the extreme events based on a 5 per year data set were extracted as shown in the following table.

	Simulated	Observed
Average	15.32	16.92
Median	12.22	14.12
Standard deviation	8.43	11.29

Table 4.9 Comparison of extreme event statistics derived from POT of calibration period

It can be seen from the above table that the extreme runoff for this catchment is underestimated using the simulated values compared to the observed values for the calibration period. However overall this catchment performs best based on the extreme statistics shown in the table above.

The differences between the observed and simulated discharges are again principally attributed to inaccuracies in the spatial and temporal distribution of rainfall data within the Broadmeadow gauge catchment. Although the data from a single synoptic station was used as the meteorological input to this rainfall-runoff model, the Broadmeadow catchment is quite large and therefore the intensity of rainfall events localised to the catchment may not be accurately represented by the temporal distribution at Dublin Airport. However, the overall distribution of events between observed and simulated discharges were very similar and it was therefore accepted that the model was accurately representing the relationship between rainfall and runoff in the catchment.

4.4.3 Simulated Discharge Data

Using the calibrated rainfall runoff model, discharges were generated for different urban percentages by varying the size of the urban extent in the Broadmeadow gauge catchment model. The size of the urban extent was related to catchment urbanisation for specific years (1973, 1995, 2000 and 2008) and was taken from Table 2.1 in Section 2, reproduced here as Table 4.10.

Year	Area	Percentage of Total Catchment Area
	(km^2)	(%)
1973	1.64	1.5
1995	3.54	3.3
2000	5.47	5.1
2008	6.85	6.4

Table 4.10 Broadmeadow Gauge Catchment Urban Data

The simulated flow data for each of the urban extents are presented in Figure 4-9.

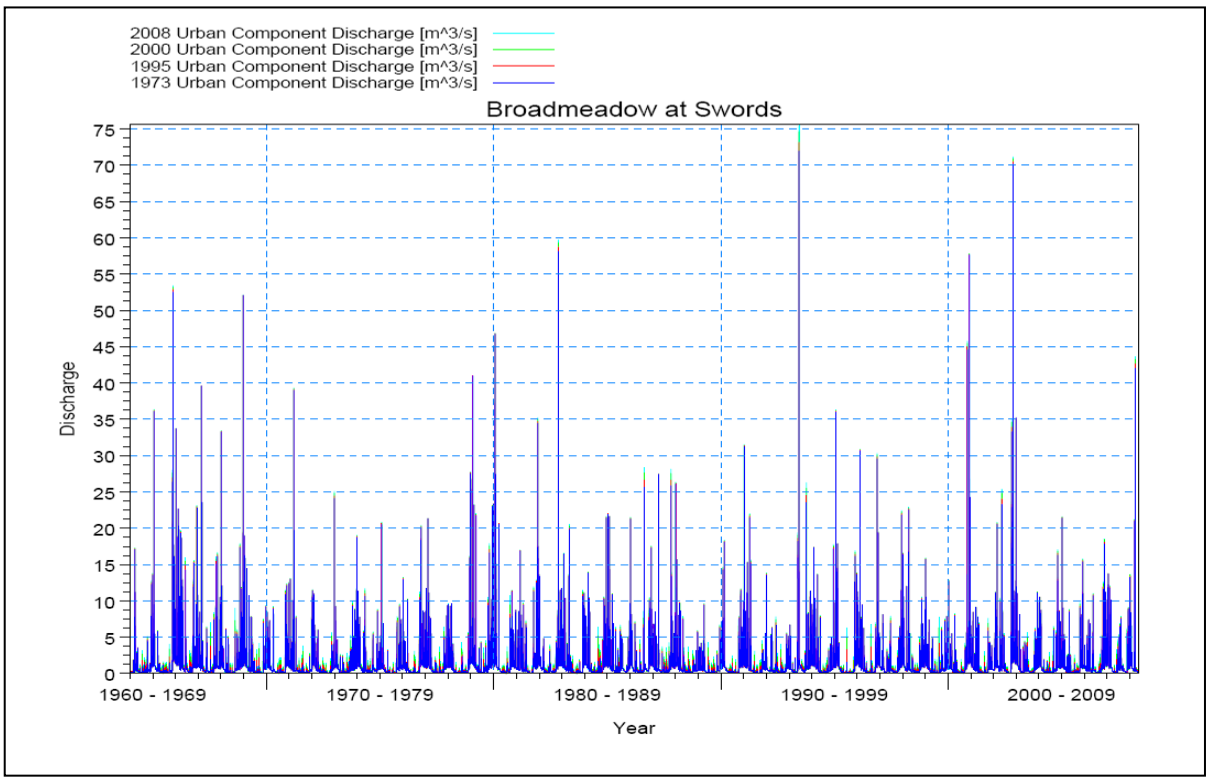


Figure 4-9 Simulated Discharge with Varying Urban Extent for Broadmeadow at Swords

5 ANALYSIS OF SIMULATED DISCHARGE DATA

A trend analysis was undertaken of the gauge data from each of the three catchments to identify any change in peak discharge frequency in the catchments which could be attributed to changes in urbanisation as described in Section 2. Any trends identified were assumed to be due to corresponding changes in catchment urbanisation, however, given the long periods of time over which the data was recorded it was considered likely that there may be other factors affecting the trend.

The simulated discharge data is composed of four separate discharge files for each gauge catchment, one each for the 1973, 1995, 2000 and 2008 urban extents. The only variation between these files is in relation to the size of the urbanised fraction of the catchment. An analysis was therefore carried out on this data to demonstrate conclusively what impact increased urbanisation has had on flood discharges. This analysis included a comparison of Annual Maxima flow series, Q_{med} estimates, and Extreme Value Analysis (EVA) results.

Annual Maxima Series

The largest flows in each year of the simulated discharged files produced for the 1973, 1995, 2000 and 2008 urban extent data sets were extracted using a statistical analysis tool to produce corresponding Annual Maxima Series (AMS). These AMS were further analysed and compared in the following sections.

Q_{med} Analysis

Q_{med} is defined as the median of the annual maxima flow for a given hydrometric gauge. Q_{med} has been calculated from the annual maxima series for each of the data sets for the three hydrometric gauges in this study and comparisons made. The ideal probability distribution for the Q_{med} value has a return period of 2 years.

Extreme Value Analysis (EVA)

Extreme value analyses were undertaken on each of the annual maxima series (AMS) extracted from the simulated discharge data files to determine discharges of known return period for each of the three gauge catchments. A range of candidate probability distributions were fitted to the data to establish the best fit. Nine distributions were available for AMS analysis along with a series of different techniques to estimate the parameters of the distributions. After consideration of the options available three distributions were selected and the different return period flows derived for each catchment. Two of the distributions are often used in Ireland for hydrological data analysis, the third is used more generally and is frequently recommended for AMS analysis of hydrological time series and has in fact proven to give the best fit to most of the data sets. The selected probability distributions and the associated techniques used to estimate the parameters of the functions were as follows:

- Generalised Extreme Value Distribution using Method of L-Moments (GEV/LMOM),
- Two parametric Log-normal Distribution using Methods of Moments fitted to logarithmic data (LN2/MOM),
- Three parametric Log-Pearson Distribution using Method of Moments fitted in logarithmic space as proposed by Beboo (LP3/MOM/LOG).

The goodness of fit of the resulting distributions was then tested using four statistical methods;

- Standardised Least Squares Criterion (SLSC)
- Probability Plot Correction Co-efficient based on sample mean values (PPCC1)
- Probability Plot Correction Co-efficient based on reduced variates (PPCC2)
- Log-Likelihood Measure (LLM).

To establish plotting positions for the data points the method suggested by Cunnane was applied both in the parameter estimation and the probability plots shown in the diagrams. The plotting positions are derived using following equation:

$$p_i = \frac{i - 0.4}{n + 0.2}$$

with i being the rank order of the individual sample and n being the total number of samples.

Further details on the methods applied in this study can be found in (DHI 2009a)

Growth Factor Analysis

The growth factors for the discharges produced by the EVA were calculated by dividing the flows by the relevant Q_{med} value determined from the Q_{med} analysis. These growth factors are then compared against the Growth Factors in relation to Q_{med} as set out in the Flood Studies Report for Ireland as well as the revised Growth Curve presented by Bruen et al.(2005). The FSR report and the study undertaken by Bruen et al. use the mean of the annual maximum series Q_{bar} as a basis for the growth curve analysis. However later studies as well as the UK Flood Estimation Handbook have shown that this gives a bias towards larger return period events and instead recommend the use of the value Q_{med}, which is the median of the annual maximum series. Thus while Q_{bar} statistically relates to an event with a return period of 2.32 years, Q_{med} has a return period of only 2 years. The growth factures obtained from the FSR and Bruen et al. have therefore been adjusted accordingly.

5.1 OWENDOHER AT WILLBROOK ROAD (GAUGE NO. 09009)

5.1.1 Annual Maxima Series

The Annual Maxima Series extracted from the discharge data generated by the model for each of 1973, 1995, 2000 and 2008 urban extents are presented in graphical format in Figure 5-1 and in tabular format in Appendix C.

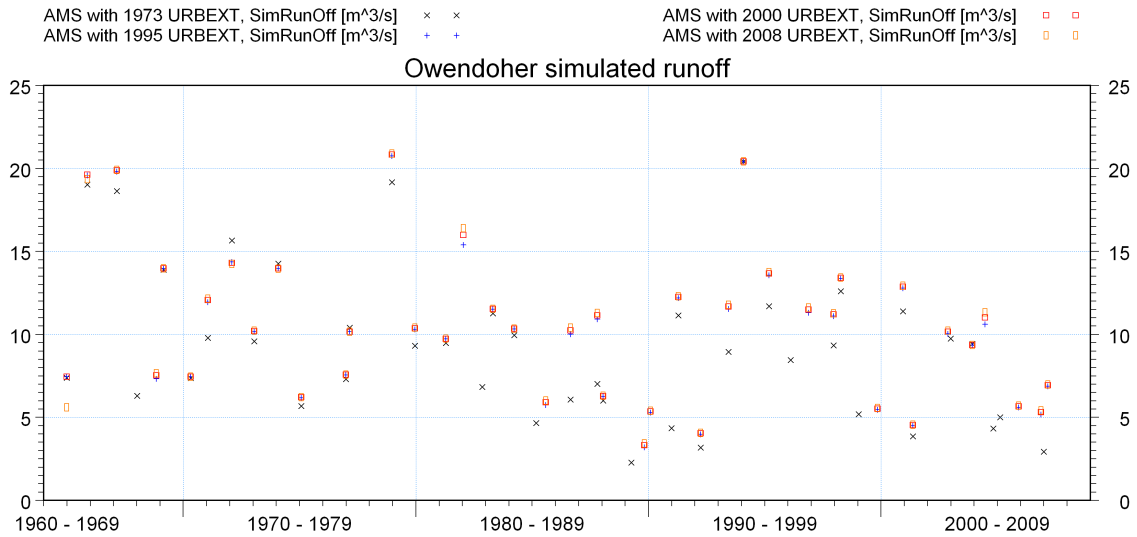


Figure 5-1 Owendoher Annual Maxima Series from Varying Urban Extent

In general, it can be seen from Figure 5-1 that a decrease in permeability due to urbanisation appears to results in an increase in extreme discharge conditions. The largest increase in urban area (as detailed in Table 4.5) occurred between 1973 and 1995 with only very moderate increases after 1995. This is reflected in Figure 5-1 which shows a jump in annual maxima values and temporal distribution between 1973 and 1995 with only slight changes after 1995. In fact most of the flow events for the 2000 and 2008 urbanisation scenarios are identical with only marginal variation for other events. There are however two peculiarities in the data set, firstly the 1986 flood event which had a significant impact on the entire Dodder Catchment does not feature with the same magnitude in this time series. A possible explanation is the distribution of rainfall in the catchment during this event, with very high rainfall in the mountainous area resulting in a large flood wave. In contrast the rainfall gauging station at Tibradden, which accounts for 54% of the rainfall in this catchment recorded significantly lower volumes (~50%) compared to the gauges at Glenmoles outside the catchment area, but in the Wicklow Mountains. The second event of particular interest is an event in 1994, which shows almost identical runoff for all urban extent simulations. This is thought to be due to very wet antecedent conditions, which gave very high runoff from both the urban and rural model components.

5.1.2 Q_{med} Analysis

The medians of the annual maxima flow series generated from the simulated discharge files for the varying urban extent data sets for the Owendoher catchment are presented in Table 5.1.

Owendoher at Willbrook Road (Gauge No. 09009)				
	1973 Urban Extent	1995 Urban Extent	2000 Urban Extent	2008 Urban Extent
Q_{med} (m^3/s)	9.33	10.31	10.34	10.40

Table 5.1 Q_{med} of Annual Maxima Series from Simulated Discharge for Owendoher

From Table 5.1 it can be seen that the Q_{med} estimate increases with increasing urbanisation. As seen in Section 5.1.1, the large increase in urban area between 1973 and 1995 results in a significant increase in the Q_{med} value (10%) with only marginal increases observed after 1995.

5.1.3 EVA of Annual Maxima Series

An EVA was carried out on the annual maxima series for each of the four simulated discharge files (1973, 1995, 2000 and 2008 urban extent) for the Owendoher gauge catchment using the statistical analysis tool. Three probability distributions as detailed at the start of this section were employed for the analysis of the AMS for each of the simulated discharges and the results are presented in the following graphs. The discharges for different events are plotted on the x-axis against the exceedence probability given on the y axis. The estimated discharges for different return period events for each of the proposed distributions are given in the tables following the probability plots. It should be noted that the return period values are the estimates derived from the probability distribution without the addition of any confidence limits as would be typically undertaken for extreme flow estimations. Some additional values on the extreme value distributions are attached in Appendix D.

Owendoher - 1973 Urban Extent

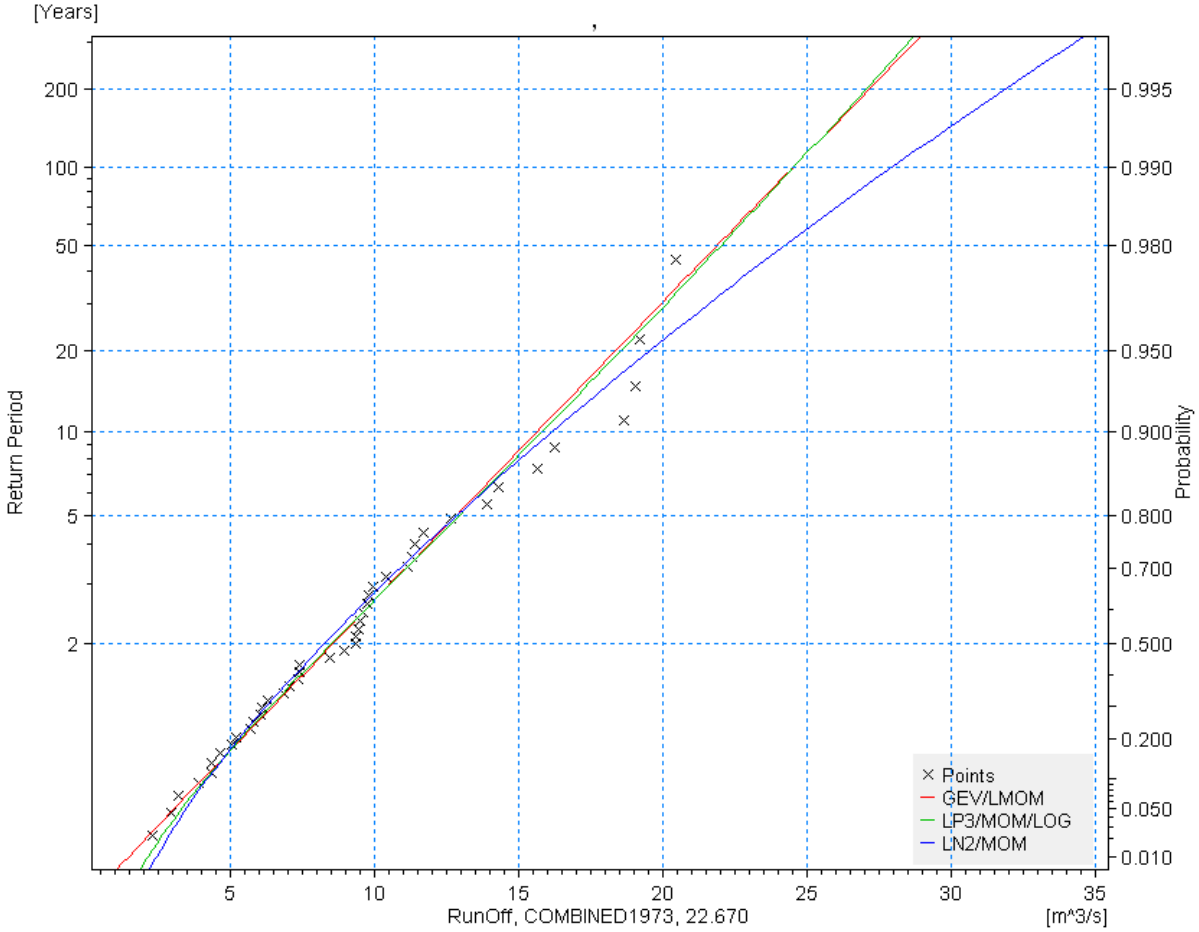


Figure 5-2 EVA of Annual Maxima Flows from Owendoher 1973 Urban Extent

		Probability Distribution		
	Return Period (Years)	**GEV/LMOM**	**LN2/MOM**	**LP3/MOM/LOG**
Discharge (m^3/s)	2	8.54	8.23	8.47
	5	12.80	12.81	12.89
	10	15.63	16.14	15.80
	20	18.35	19.54	18.54
	50	21.87	24.23	22.00
	100	24.52	27.96	24.55

Table 5.2 Estimated Discharge Values for Different RTPs based on 1973 Urban Extent

Owendoher - 1995 Urban Extent

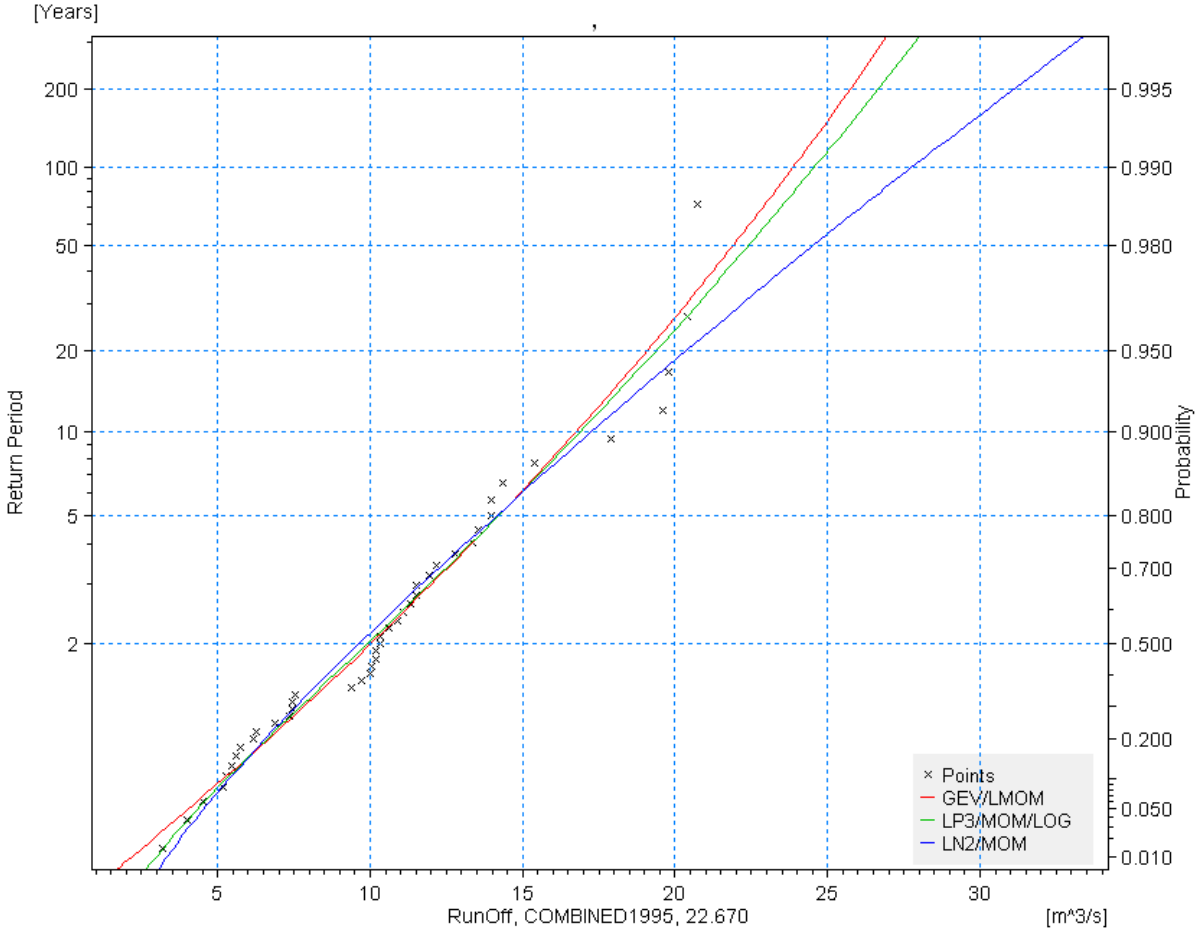


Figure 5-3 EVA of Annual Maxima Flows from Owendoher 1995 Urban Extent

		Probability Distribution		
	Return Period (Years)	**GEV/LMOM**	**LN2/MOM**	**LP3/MOM/LOG**
Discharge (m^3/s)	2	10.02	9.62	9.89
	5	14.19	14.12	14.20
	10	16.76	17.26	16.91
	20	19.08	20.36	19.38
	50	21.90	24.54	22.41
	100	23.88	27.78	24.58

Table 5.3 Estimated Discharge Values for Different RTPs based on 1995 Urban Extent

Owendoher - 2000 Urban Extent

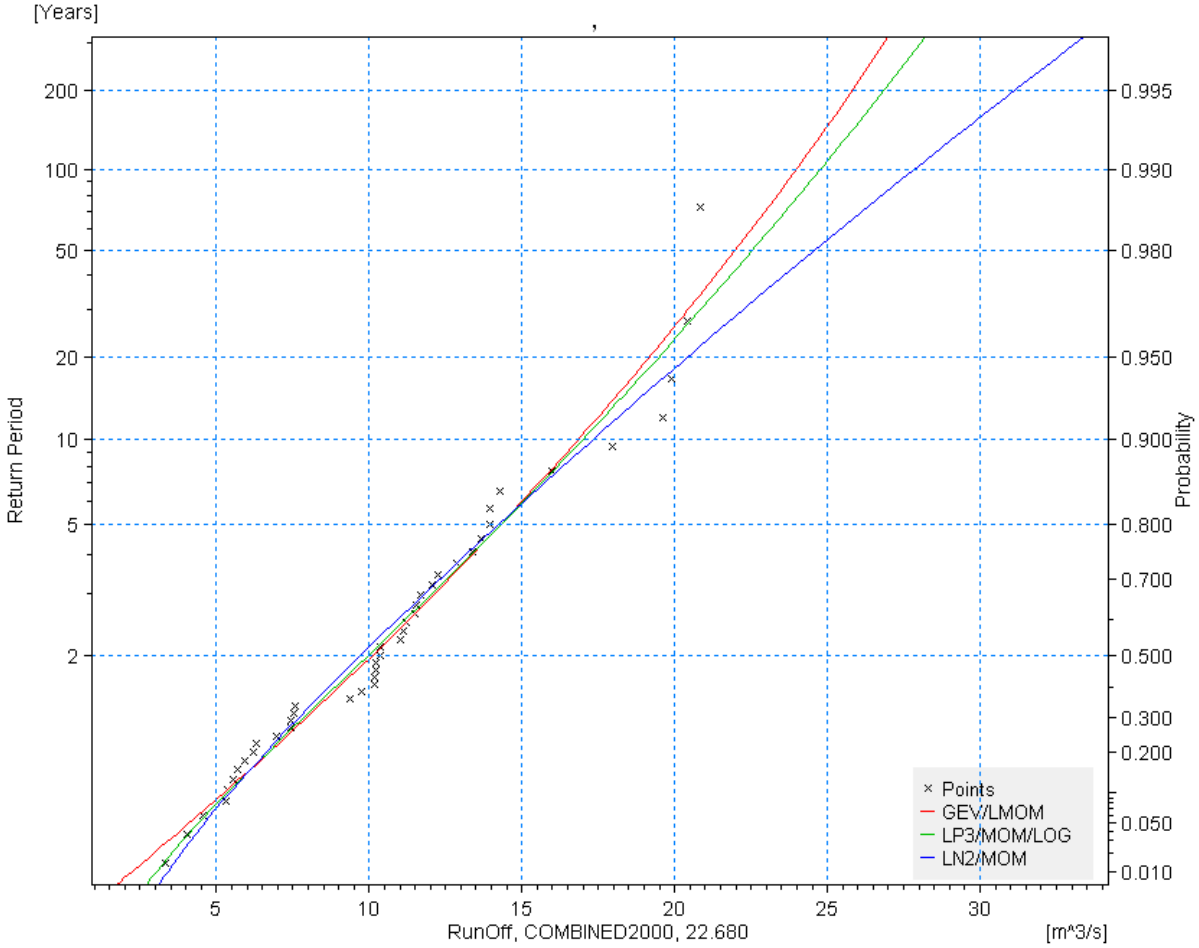


Figure 5-4 EVA of Annual Maxima Flows from Owendoher 2000 Urban Extent

		Probability Distribution		
	Return Period (Years)	GEV/LMOM	LN2/MOM	LP3/MOM/LOG
Discharge (m^3/s)	2	10.11	9.72	9.97
	5	14.29	14.22	14.30
	10	16.86	17.34	17.01
	20	19.18	20.44	19.49
	50	21.99	24.59	22.56
	100	23.97	27.82	24.75

Table 5.4 Estimated Discharge Values for Different RTPs based on 2000 Urban Extent

Owendoher - 2008 Urban Extent

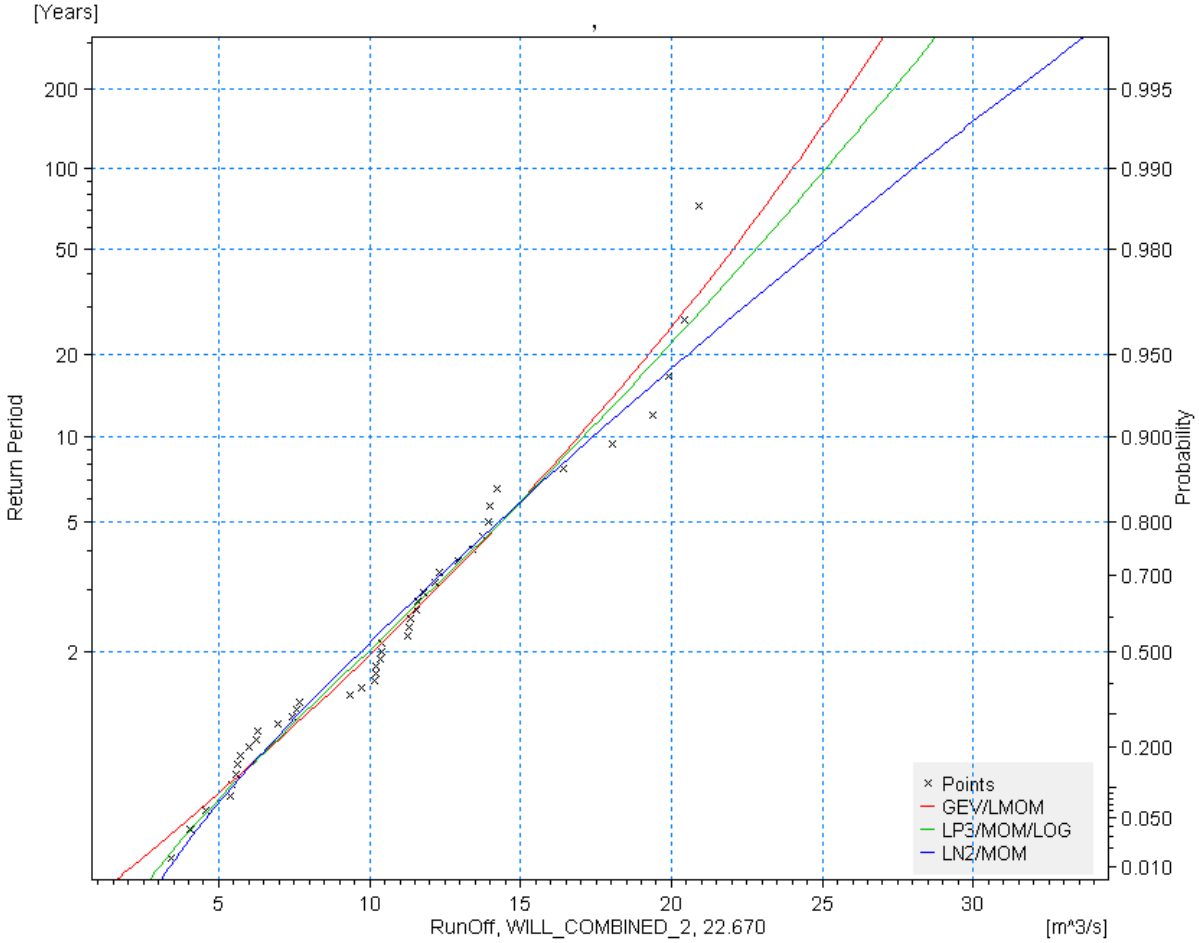


Figure 5-5 EVA of Annual Maxima Flows from Owendoher 2008 Urban Extent

		Probability Distribution		
	Return Period (Years)	**GEV/LMOM**	**LN2/MOM**	**LP3/MOM/LOG**
Discharge (m^3/s)	2	10.13	9.71	9.95
	5	14.34	14.24	14.32
	10	16.92	17.40	17.09
	20	19.24	20.53	19.65
	50	22.05	24.74	22.82
	100	24.01	28.01	25.10

Table 5.5 Estimated Discharge Values for Different RTPs based on 2008 Urban Extent

Owendoher – EVA Summary

Based on the Goodness-of-fit statistics the three parametric Log Pearson Function fits the simulated data best. The different return period flows estimated by this probability distribution for each of the simulated time series covering the urban extents corresponding to the years 1973, 1995, 2000 and 2008 are summarised in Table 5.6.

		Probability Distribution - LP3/MOM/LOG			
	Return Period (Years)	**1973**	**1995**	**2000**	**2008**
Discharge (m^3/s)	2.0	8.47	9.89	9.97	9.95
	5.0	12.89	14.20	14.30	14.32
	10.0	15.80	16.91	17.01	17.09
	20.0	18.54	19.38	19.49	19.65
	50.0	22.00	22.41	22.56	22.82
	100.0	24.55	24.58	24.75	25.10

Table 5.6 Summary of Different Return Period Discharge Values based on AMS from Owendoher Simulated Discharge

It can be seen from Table 5.6 that for lower return periods (< 20 years) the Owendoher extreme flows from the 1973, 1995, 2000 and 2008 data sets get progressively larger. This corresponds with the increasing urban extent from 1973 to 2008 and indicates a degree of correlation between the urban extent in the rainfall runoff model, and the magnitude of the estimated extreme flow. The increase is less pronounced between 2000 and 2008 than in previous intervals, which correlates with the very marginal increase in urbanisation for this period. However the increase in urban extent does not appear to result in a significant increase in extreme events of 50 or 100 year return period and above. This can be accounted for by the fact that the increase in discharge associated with increased urbanisation between 1973 and 2008 accounts for 16% of a 2 year return period flood event, but only accounts for an increase of 2% for a 100 year event. Thus any change in the magnitude of the more extreme events due to the levels of increased urbanisation that have occurred in the Owendoher catchment will be marginal.

5.1.4 Growth Factor Analysis

Section 5.1.2 shows the Q_{med} value from the simulated discharge files to increase with increasing urbanisation. The Extreme Value Analysis described in Section 5.1.3 further determines that the magnitude of the extreme events also change in line with increasing urban area. A Growth Factor Analysis was therefore undertaken to determine whether the magnitude of the extreme events change in accordance with the recommended Flood Studies Report (FSR) growth factors, suitably adjusted to change the base from Q_{bar} to Q_{med}. To complete this analysis the discharges estimated using the three parametric Log Pearson probability distribution from Section 5.1.3 for each of the 1973, 1995, 2000 and 2008 data sets were divided by the relevant Q_{med} value to produce growth factors. The resulting growth factors are presented in Table 5.7 along with the recommended FSR Q_{med} growth factors for Ireland and the suggested growth factors for Eastern catchments established by (Bruen et al. 2005).

		Growth Factor					
	Return Period (Years)	**1973**	**1995**	**2000**	**2008**	**FSR**	**Bruen et al.**
Discharge (m^3/s)	2.0	0.91	0.96	0.96	0.96	1.00	1.00
	5.0	1.38	1.38	1.38	1.38	1.26	1.48
	10.0	1.69	1.64	1.65	1.64	1.44	1.82
	20.0	1.99	1.88	1.89	1.89	1.62	2.13
	50.0	2.36	2.17	2.18	2.19	1.86	2.53
	100.0	2.63	2.38	2.39	2.41	2.06	2.84

Table 5.7 Discharge Growth Factors from Simulated Data for Owendoher at Willbrook Road

When compared against the FSR (Q_{med}) growth factors presented in Table 5.7, those generated from the flow files tend to be between the FSR factors and the growth factors suggested by Bruen et al based on observed discharges. While the growth factor suggested originally by the FSR for Ireland would yield a factor of 2.06 for a 1 in 100 year event, compared to the 1973 simulations this would be equivalent to the growth factor for an event with a return period of between 20 and 50years. In contrast Bruen suggests a growth factor of ~ 2.8 for a 1 in 100 year event, while the analysis of the 1973 model output indicates a growth factor of 2.6. For more recent urbanisation scenarios the growth curve flattens slightly, which is consistent with the expectation that in higher return period events the ground becomes saturated and the runoff response of the whole catchment is similar to that from an impermeable (urban) surface, while the Q_{med} base value increases with increasing urbanisation.

5.2 GRIFFEEN AT LUCAN (GAUGE NO. 09002)

5.2.1 Annual Maxima Series

The Annual Maxima Series from the discharge data generated from the model for the estimated 1973, 1995, 2000 and 2008 urban extents are presented in graphical format in Figure 5-6 and in tabular format in Appendix C.

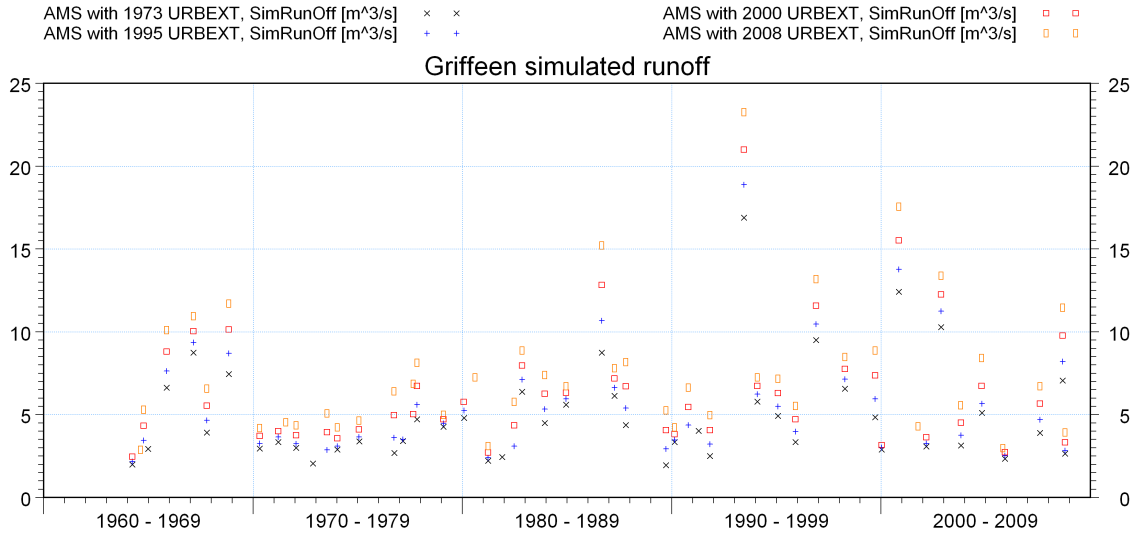


Figure 5-6 Griffeen Annual Maxima Series from Varying Urban Extent

Figure 5-6 demonstrates that the significant increases in the urban extent observed in the Griffeen catchment and incorporated in the rainfall-runoff model produce markedly higher annual maximum discharges. In some instances the dates of the annual maxima events have also changed as a consequence of the increased urbanisation which means that a different rainfall event has produced the maximum flood event for that year.

5.2.2 Q_{med} Analysis

The median of the annual maxima flow series (Q_{med}) generated from the simulated discharge files for the varying urban extent data sets for the Griffeen catchment are presented in Table 5.8.

Griffeen at Lucan (Gauge No. 09002)				
	1973 Urban Extent	**1995 Urban Extent**	**2000 Urban Extent**	**2008 Urban Extent**
Q_{med} (m^3/s)	3.97	4.56	5.50	6.67

Table 5.8 Q_{med} of Annual Maxima Series from Simulated Discharge for Griffeen

It can be seen from Table 5.8 that the Q_{med} values get larger as the extent of urbanisation within the catchment increases. The increase in urbanisation from just over 5% in 1973 to 25% in 2008 has a major impact on the median of the runoff in this catchment with an increase in Q_{med} of close to 70% at the Lucan gauging station.

5.2.3 EVA of Annual Maxima Series

An EVA was carried out on the annual maxima series for each of the four simulated discharge files (1973, 1995, 2000 and 2008 urban extents) for the Griffeen gauge catchment using the statistical analysis tool. The fit of the three probability distributions detailed at the start of section 5 to each AMS for the simulated discharges are presented in the following graphs. The discharges for different events are plotted on the x-axis while the exceedence probability is plotted on the y axis. The estimated discharges for different return period events for each of the proposed distributions are given in the tables following the probability plots. It should be noted that the return period values are the estimates derived from the probability distribution without the addition of any confidence limits as would be typically undertaken for flow estimations. Some additional return period values from the extreme value distributions are attached in Appendix D

Griffeen - 1973 Urban Extent

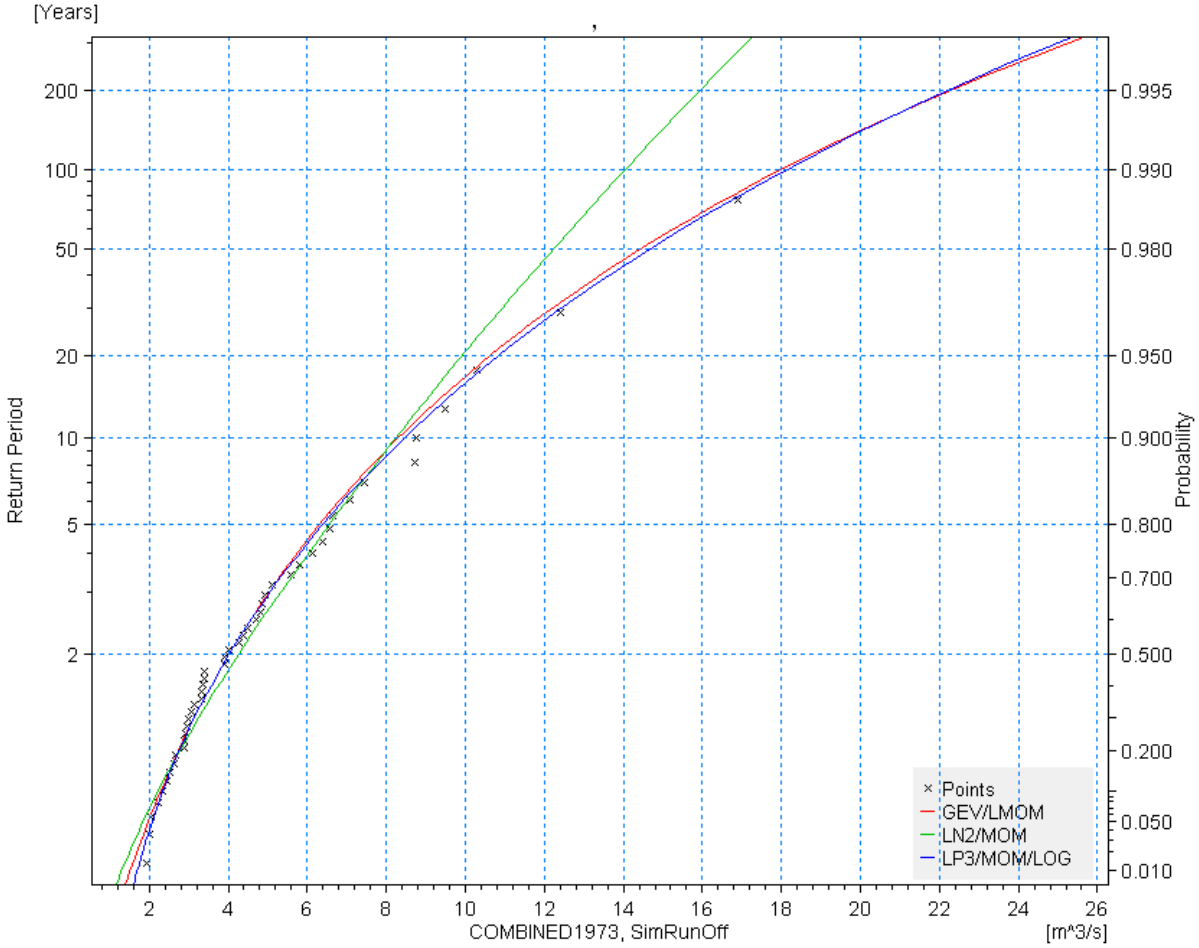


Figure 5-7 EVA of Annual Maxima Flows from Griffeen 1973 Urban Extent

		Probability Distribution		
	Return Period (Years)	**GEV/LMOM**	**LN2/MOM**	**LP3/MOM/LOG**
Discharge (m^3/s)	2	4.04	4.28	4.03
	5	6.32	6.57	6.40
	10	8.29	8.23	8.45
	20	10.61	9.91	10.83
	50	14.40	12.21	14.63
	100	17.97	14.04	18.11

Table 5.9 Estimated Discharge Values for Different RTPs based on 1973 Urban Extent

Griffeen - 1995 Urban Extent

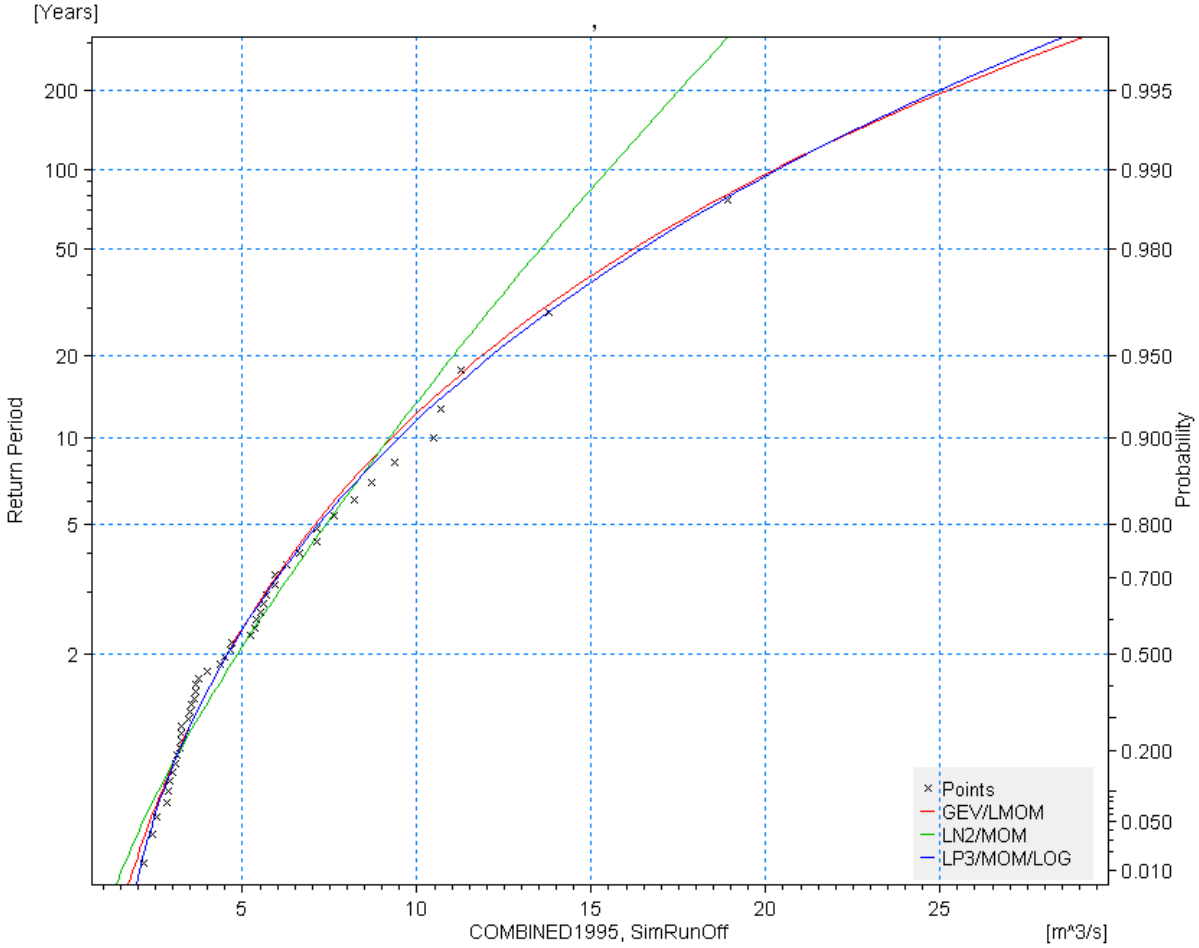


Figure 5-8 EVA of Annual Maxima Flows from Griffeen 1995 Urban Extent

		Probability Distribution		
	Return Period (Years)	**GEV/LMOM**	**LN2/MOM**	**LP3/MOM/LOG**
Discharge (m^3/s)	2	4.57	4.87	4.57
	5	7.08	7.40	7.19
	10	9.26	9.21	9.46
	20	11.86	11.03	12.12
	50	16.16	13.52	16.39
	100	20.23	15.48	20.32

Table 5.10 Estimated Discharge Values for Different RTPs based on 1995 Urban Extent

Griffeen - 2000 Urban Extent

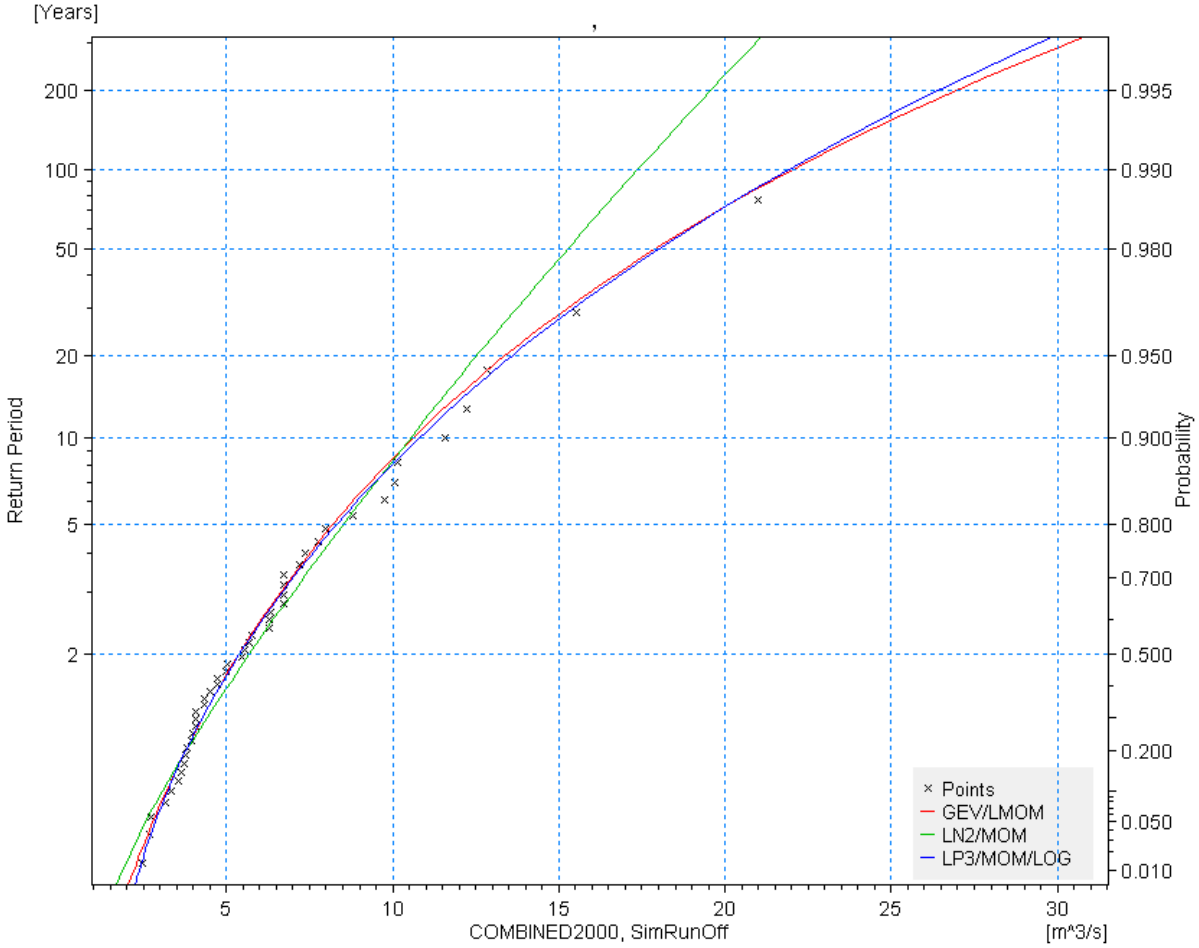


Figure 5-9 EVA of Annual Maxima Flows from Griffeen 2000 Urban Extent

		Probability Distribution		
	Return Period (Years)	**GEV/LMOM**	**LN2/MOM**	**LP3/MOM/LOG**
Discharge (m^3/s)	2	5.39	5.70	5.40
	5	8.21	8.53	8.33
	10	10.60	10.53	10.79
	20	13.38	12.53	13.59
	50	17.86	15.24	17.96
	100	22.01	17.37	21.89

Table 5.11 Estimated Discharge Values for Different RTPs based on 2000 Urban Extent

Griffeen - 2008 Urban Extent

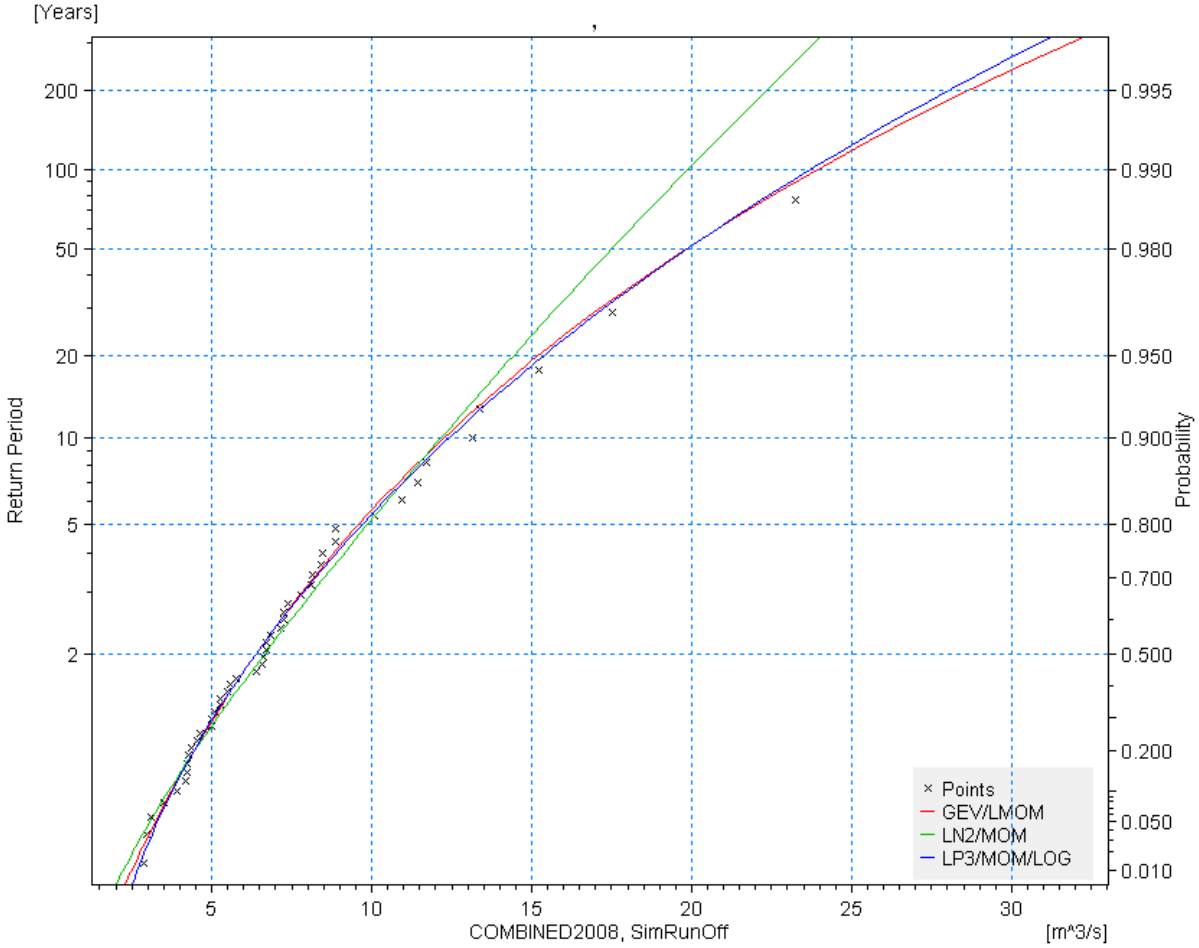


Figure 5-10 EVA of Annual Maxima Flows from Griffeen 2008 Urban Extent

		Probability Distribution		
	Return Period (Years)	**GEV/LMOM**	**LN2/MOM**	**LP3/MOM/LOG**
Discharge (m^3/s)	2	6.38	6.66	6.39
	5	9.61	9.89	9.73
	10	12.24	12.16	12.41
	20	15.20	14.42	15.36
	50	19.79	17.48	19.82
	100	23.91	19.87	23.69

Table 5.12 Estimated Discharge Values for Different RTPs based on 2008 Urban Extent

Griffeen - Summary

Based on the Goodness-of-fit statistics the three parametric Log Pearson Function provides the best fit to the simulated data. The different return period flows estimated by this probability distributions for each of the simulated time series covering the estimated urban extents for the years 1973, 1995, 2000 and 2008 are summarised in Table 5.13.

		Probability Distribution - LP3/MOM/LOG			
	Return Period (Years)	**1973**	**1995**	**2000**	**2008**
Discharge (m^3/s)	2.0	4.03	4.57	5.40	6.39
	5.0	6.40	7.19	8.33	9.73
	10.0	8.45	9.46	10.79	12.41
	20.0	10.83	12.12	13.59	15.36
	50.0	14.63	16.39	17.96	19.82
	100.0	18.11	20.32	21.89	23.69

Table 5.13 Summary of Different Return Period Discharge Values based on AMS from Griffeen Simulated Discharge

It can be seen from Table 5.13 that there is a progressive increase in the magnitude of the flows as the degree of urbanisation increases with the 2008 Griffeen data set producing the largest estimated flows. This increase in magnitude of the return period flows corresponds to the urban extent increasing from 5.6% in 1973 to 24.4% in 2008. As was observed in the Owendoher data set the percentage increase in extreme runoff reduces with increasing return period. In the Griffeen catchment an increase of close to 70% in Q_{med} from 1973 to 2008 reduces to 30% increase for the 1 in 100 year event over the same period. Nonetheless what could have been considered a 1 in 100 year discharge in the 1973 scenario is reduced to a 35 year return period discharge by 2008.

5.2.4 Growth Factor Analysis

Table 5.8 in Section 5.2.2 showed that the Q_{med} value from the simulated discharge files increased with increasing urbanisation. The Extreme Value Analysis described in Section 5.2.3 further determined that the magnitude of the extreme events changes in line with increasing extent of urbanisation. A Growth Factor Analysis undertaken to determine whether the magnitude of the extreme events change in accordance with the recommended Flood Studies Report (FSR) growth factors. To complete this analysis the discharges estimated using the three parametric Log Pearson probability distribution from Section 5.2.3 for each of the 1973, 1995, 2000 and 2008 data sets were divided by the relevant Q_{med} value to produce growth factors. The resulting growth factors are presented in Table 5.14 along with the recommended FSR Q_{med} growth factors for Ireland and the suggested growth factors for Eastern catchments established by (Bruen et al. 2005) suitably amended to account for the change in reference flow from Q_{bar} to Q_{med}.

		Growth Factor					
	Return Period (Years)	1973	1995	2000	2008	FSR	Bruen et al.
Discharge (m^3/s)	2.0	1.01	1.00	0.98	0.96	1.00	1.00
	5.0	1.61	1.58	1.51	1.46	1.26	1.48
	10.0	2.13	2.07	1.96	1.86	1.44	1.82
	20.0	2.73	2.66	2.47	2.30	1.62	2.13
	50.0	3.69	3.59	3.26	2.97	1.86	2.53
	100.0	4.56	4.45	3.98	3.55	2.06	2.84

Table 5.14 Discharge Growth Factors from Simulated Data for Griffeen at Lucan

When compared against the FSR growth factors presented in Table 5.14, those generated from the numerical modelling are generally significantly higher than the FSR factors for the same return periods. In Bruen et al. (2005) the EV1 distribution is plotted against the 25 years of records from the same catchment. The authors derive a growth factor equivalent to 2.84 for this catchment ignoring three outliers in the data set, which arguably would lead in their own right to growth factors of close to 4 for the same return period. It can therefore be stated that, while the growth factors given by the FSR for Ireland seem to differ significantly the results from the simulation are still in line with observations made elsewhere and an analysis of the same catchment made by another author. As with the Owendoher catchment it is interesting to note that the growth factors tend to decrease with increasing urbanisation of the catchment. This is consistent with the expectation that in higher return period events the ground becomes saturated and the runoff response is similar to that from an impermeable (urban) surface. Therefore the effect of increased urbanisation has less impact on higher return period events.

5.3 BROADMEADOW AT SWORDS (GAUGE NO. 08008)

5.3.1 Annual Maxima Series

The Annual Maxima Series of the discharge data generated from the model for each of the estimated 1973, 1995, 2000 and 2008 urban extents are presented in graphical format in Figure 5-11 and in tabular format in Appendix C.

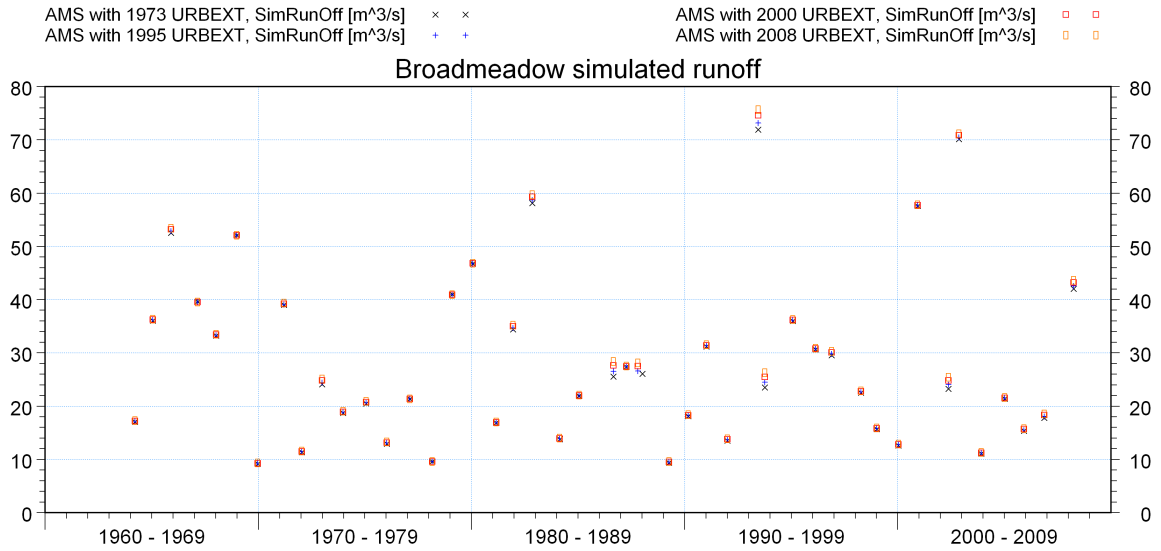


Figure 5-11 Broadmeadow Annual Maxima Series from Varying Urban Extent

Figure 5-11 demonstrates that the small increase in the urban extent observed in the Broadmeadow catchment produces relatively little change in the annual maximum discharges produced by the rainfall run-off model.

5.3.2 Q_{med} Analysis

The median of the annual maxima flow series (Q_{med}) generated from the simulated discharge files for the varying urban extent data sets for the Broadmeadow gauge catchment are presented in Table 5.15.

Broadmeadow at Swords (Gauge No. 08008)				
	1973 Urban Extent	**1995 Urban Extent**	**2000 Urban Extent**	**2008 Urban Extent**
Q_{med} (m^3/s)	23.52	24.45	24.82	25.39

Table 5.15 Q_{med} of Annual Maxima Series from Simulated Discharge for Broadmeadow

In this catchment the degree of urbanisation has increased from 1.5% in 1973 to 6.3% in 2008 which implies that the urbanised area has more than quadrupled during this time. However the actual overall urban fraction is still very small, nonetheless it can be seen from Table 5.15 that the Q_{med} values increase as the degree of urbanisation increases.

5.3.3 EVA of Annual Maxima Series

An EVA was carried out on the annual maxima series for each of the four simulated discharge files (1973, 1995, 2000 and 2008 urban extents) for the Broadmeadow gauge catchment using the statistical analysis tool. The three probability distributions detailed at the start of section 5 were applied to each AMS of the simulated discharges as presented in the following graphs. The discharges for different events are plotted on the x-axis against the exceedence probability on the y axis. The estimated discharges for different return period events for each of the proposed distributions are given in the tables below the probability plots. It should be noted that the return period values are the estimates derived from the probability distribution without the addition of any confidence limits as would be typically undertaken for flow estimations. Some additional return period discharges derived from the extreme value distributions are attached in Appendix D

Broadmeadow - 1973 Urban Extent

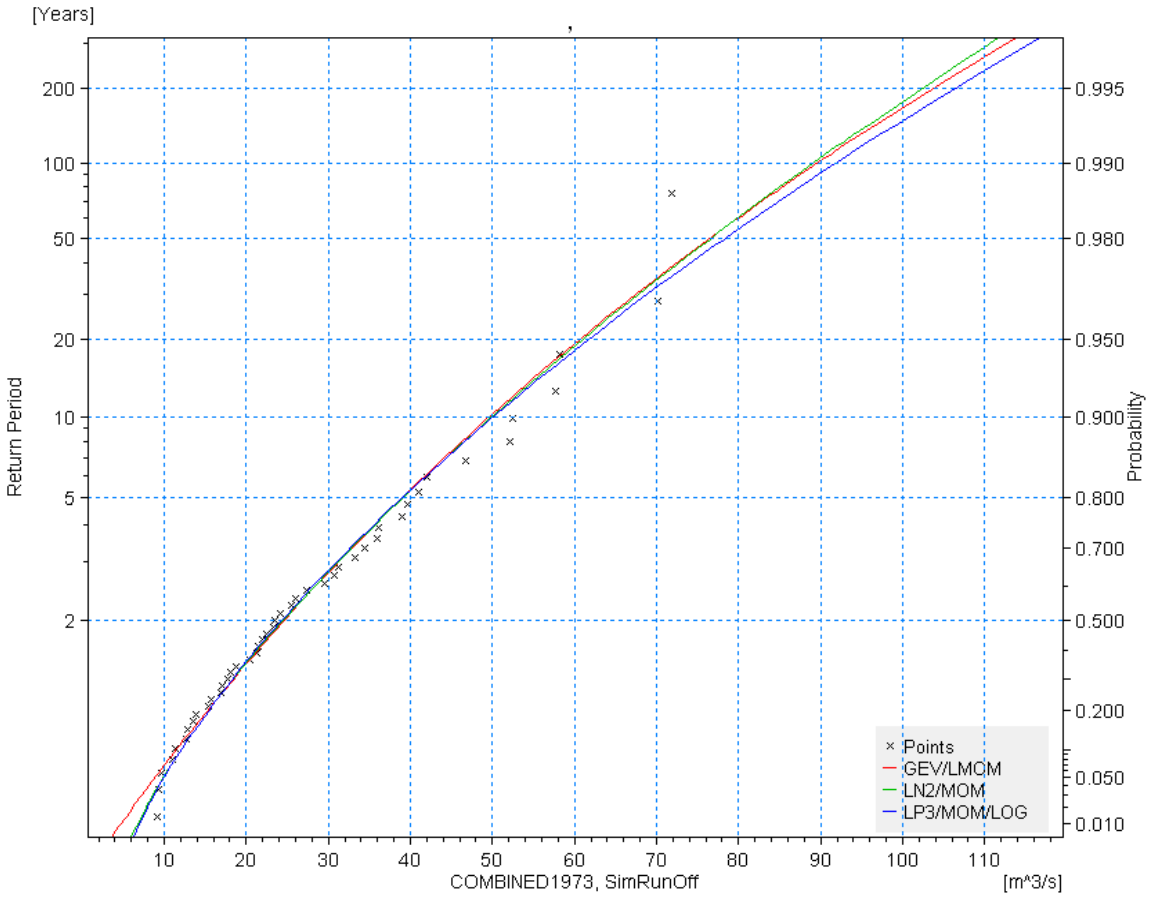


Figure 5-12 EVA of Annual Maxima Flows from Broadmeadow 1973 Urban Extent

		Probability Distribution		
	Return Period (Years)	**GEV/LMOM**	**LN2/MOM**	**LP3/MOM/LOG**
Discharge (m^3/s)	2	24.72	24.55	24.38
	5	39.05	39.15	39.07
	10	49.65	49.97	50.19
	20	60.75	61.13	61.84
	50	76.60	76.69	78.39
	100	89.68	89.20	91.94

Table 5.16 Estimated Discharge Values for Different RTPs based on 1973 Urban Extent

Broadmeadow - 1995 Urban Extent

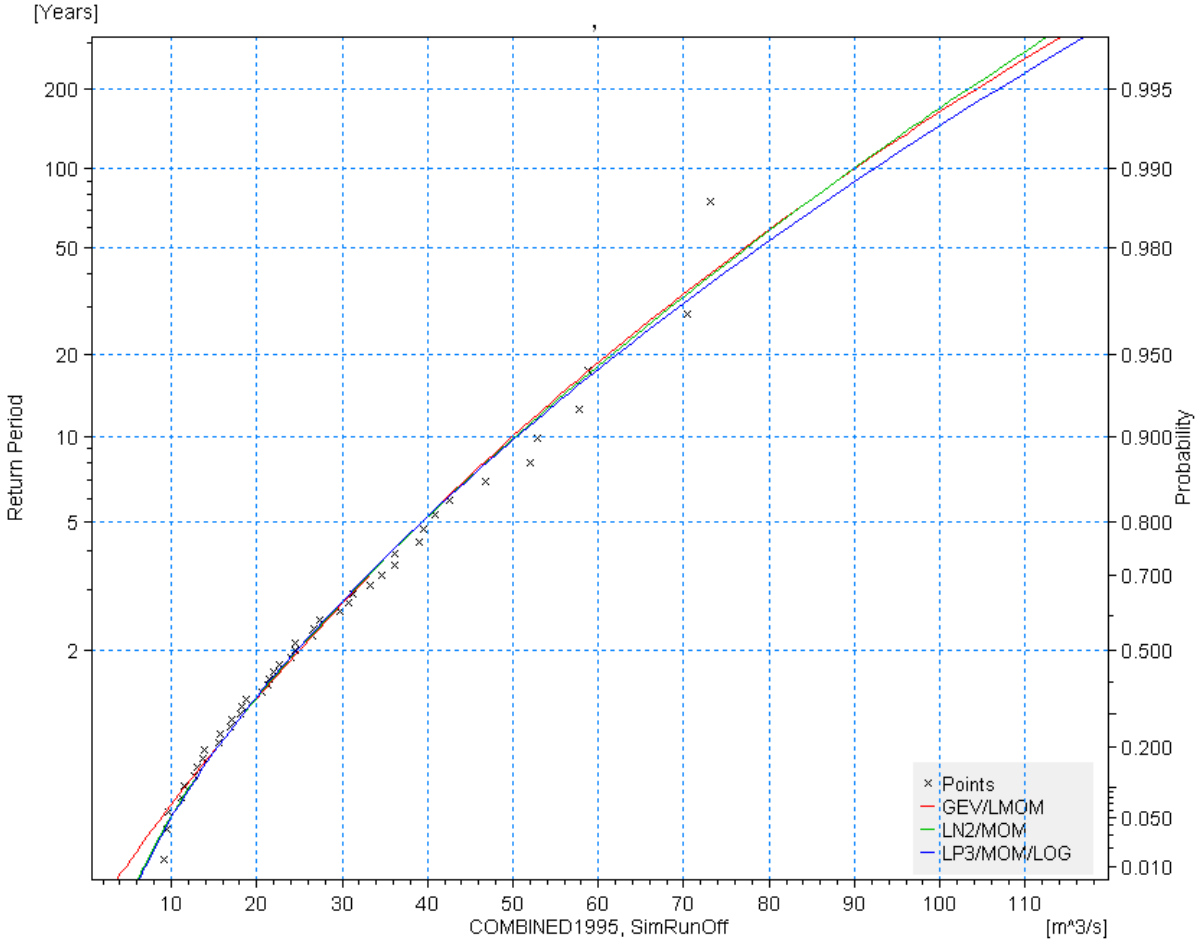


Figure 5-13 EVA of Annual Maxima Flows from Broadmeadow 1995 Urban Extent

		Probability Distribution		
	Return Period (Years)	**GEV/LMOM**	**LN2/MOM**	**LP3/MOM/LOG**
Discharge (m^3/s)	2	24.94	24.74	24.60
	5	39.36	39.46	39.39
	10	50.01	50.36	50.55
	20	61.13	61.60	62.22
	50	76.98	77.28	78.75
	100	90.02	89.89	92.25

Table 5.17 Estimated Discharge Values for Different RTPs based on 1995 Urban Extent

Broadmeadow - 2000 Urban Extent

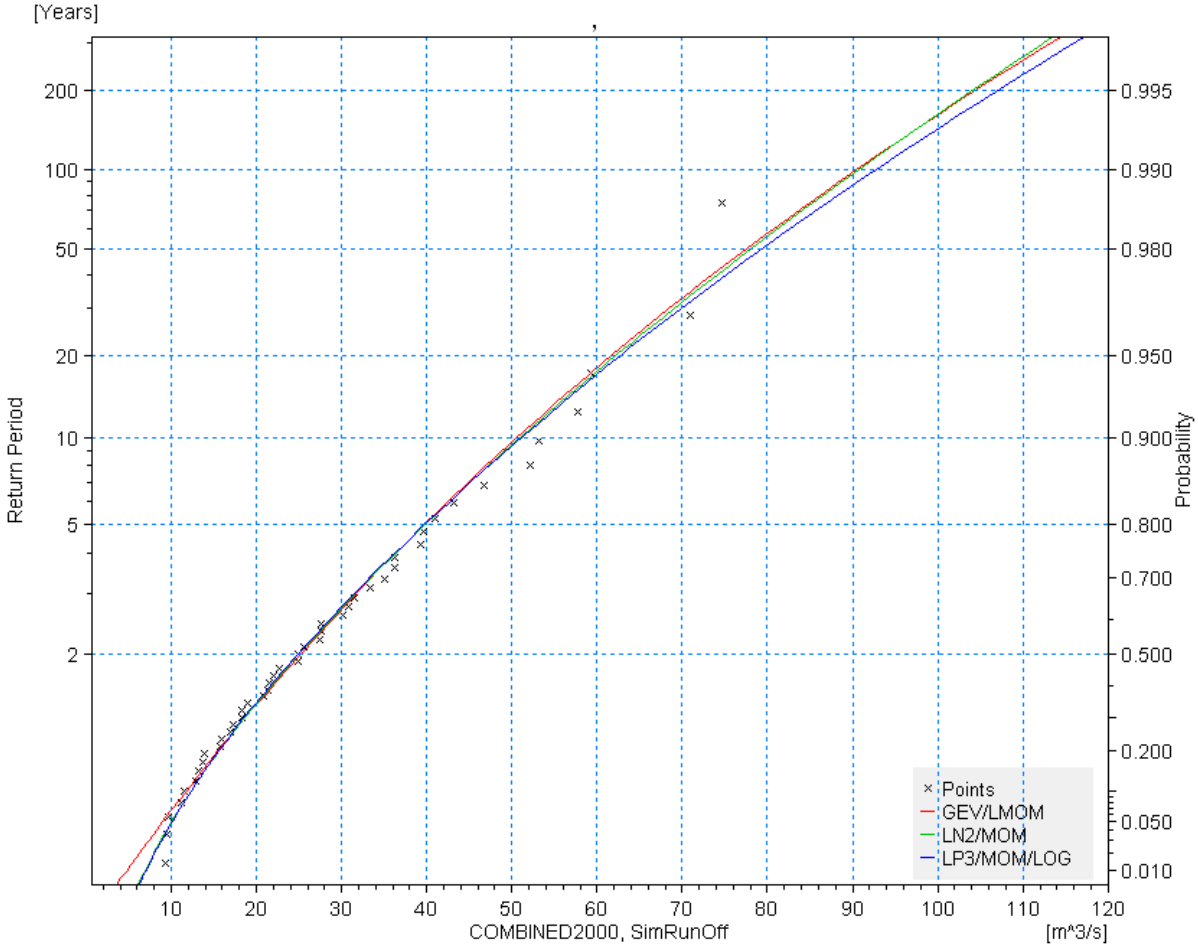


Figure 5-14 EVA of Annual Maxima Flows from Broadmeadow 2000 Urban Extent

		Probability Distribution		
		GEV/LMOM	**LN2/MOM**	**LP3/MOM/LOG**
Discharge (m^3/s)	2	25.18	24.95	24.83
	5	39.71	39.80	39.74
	10	50.41	50.80	50.95
	20	61.57	62.14	62.66
	50	77.42	77.95	79.20
	100	90.44	90.68	92.68

Table 5.18 Estimated Discharge Values for Different RTPs based on 2000 Urban Extent

Broadmeadow - 2008 Urban Extent

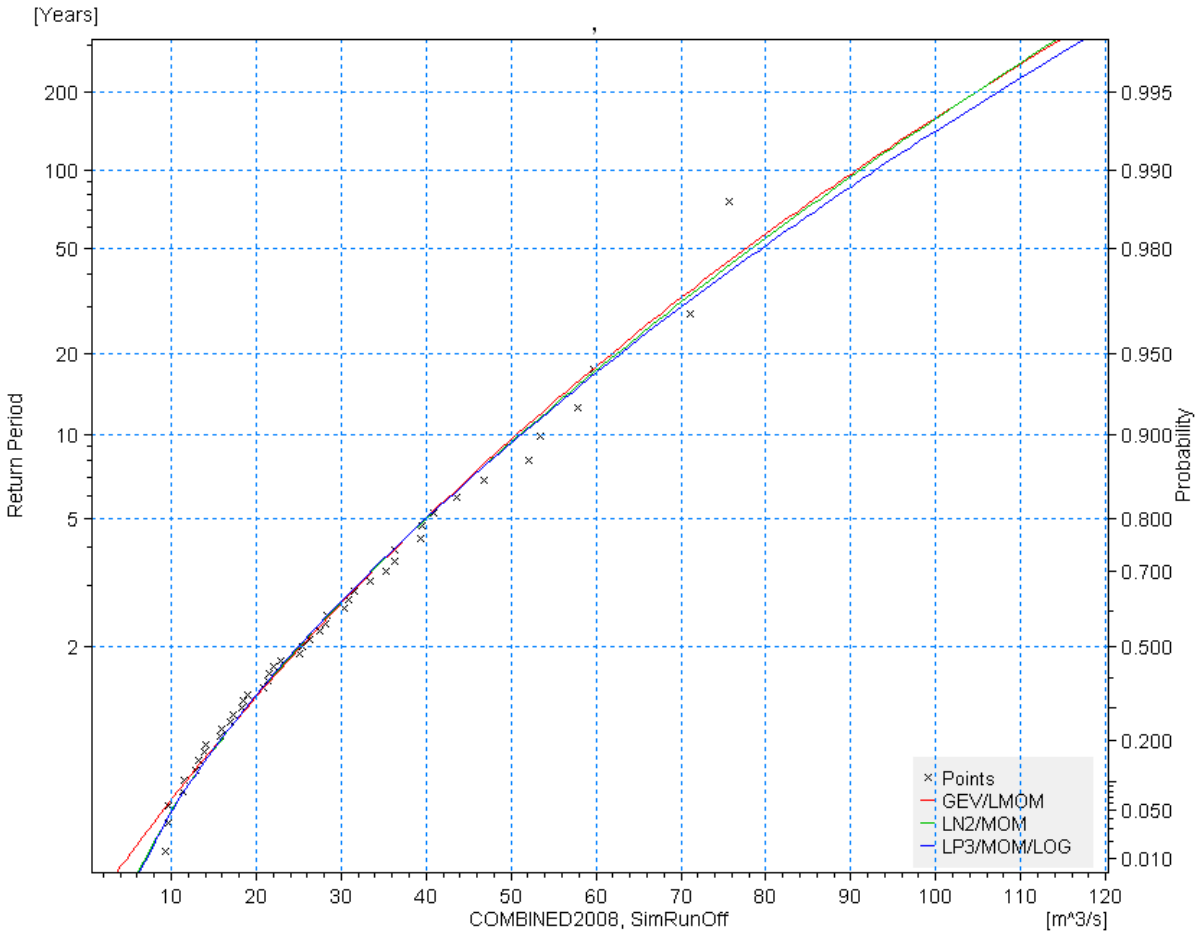


Figure 5-15 EVA of Annual Maxima Flows from Broadmeadow 2008 Urban Extent

		Probability Distribution		
	Return Period (Years)	**GEV/LMOM**	**LN2/MOM**	**LP3/MOM/LOG**
Discharge (m^3/s)	2	25.35	25.10	24.99
	5	39.96	40.04	39.99
	10	50.70	51.11	51.25
	20	61.88	62.52	62.98
	50	77.74	78.43	79.54
	100	90.75	91.24	93.01

Table 5.19 Estimated Discharge Values for Different RTPs based on 2008 Urban Extent

Broadmeadow - Summary

Based on the Goodness-of-fit statistics the three parametric Log Pearson Function fits the simulated data best. The different return period flows estimated using this probability distribution for each of the simulated time series representing the urban extents for the years 1973, 1995, 2000 and 2008 are summarised in Table 5.20.

		Probability Distribution - LP3/MOM/LOG			
	Return Period (Years)	**1973**	**1995**	**2000**	**2008**
Discharge (m^3/s)	2.0	24.55	24.74	24.95	25.10
	5.0	39.15	39.46	39.80	40.04
	10.0	49.97	50.36	50.80	51.11
	20.0	61.13	61.60	62.14	62.52
	50.0	76.69	77.28	77.95	78.43
	100.0	89.20	89.89	90.68	91.24

Table 5.20 Summary of Different Return Period Discharge Values based on AMS from Broadmeadow Simulated Discharge

It can be seen from Table 5.20 that the discharges increase progressively from the 1973 scenario to 2008 in line with increased urbanisation of the catchment. The difference in flows between the 1973 data set and the 2008 data set is small which correlates with the relatively small increase in urbanisation (~2%) across the Broadmeadow catchment over this period.

5.3.4 Growth Factor Analysis

It can be seen from Section 5.3.2 that the Q_{med} value from the simulated discharge files increases with increasing urbanisation. The Extreme Value Analysis described in Section 5.3.3 further establishes that the magnitude of the extreme events increase in line with increasing urban areas. A Growth Factor Analysis was therefore undertaken to determine whether the magnitude of the change in extreme events observed was in accordance with the Flood Studies Report (FSR) Q_{med} growth factors. To complete this analysis the return period discharges estimated using the three parametric Log Pearson probability distribution outlined in Section 5.3.3 for each of the 1973, 1995, 2000 and 2008 data sets were divided by the relevant Q_{med} value to produce growth factors. The resulting growth factors are presented in Table 5.21 along with the recommended FSR growth factors for Ireland and the suggested growth factors for Eastern catchments established by (Bruen et al. 2005) suitably amended to account for the change in reference flow from Q_{bar} to Q_{med}.

		Growth Factor					
	Return Period (Years)	**1973**	**1995**	**2000**	**2008**	**FSR**	**Bruen et al.**
Discharge (m^3/s)	2.0	1.04	1.01	1.01	0.99	1.00	1.00
	5.0	1.66	1.61	1.60	1.58	1.26	1.48
	10.0	2.12	2.06	2.05	2.01	1.44	1.82
	20.0	2.60	2.52	2.50	2.46	1.62	2.13
	50.0	3.26	3.16	3.14	3.09	1.86	2.53
	100.0	3.79	3.68	3.65	3.59	2.06	2.84

Table 5.21 Discharge Growth Factors from Simulated Data for Broadmeadow at Swords

When compared against the modified FSR growth factors presented in Table 5.21, the growth factors derived from the modelling undertaken in this study were found to be significantly higher than the FSR factors for the same return periods. As with the analysis for the Owendoher and Griffeen catchments the calculated growth factors decrease with increasing urbanisation. This is consistent with the expectations that in higher return period events the ground becomes saturated and the runoff response is similar to that from an impermeable (urban) surface, and that increasing urbanisation increased the Q_{med} flow therefore the effect of increased urbanisation has less impact on higher return period growth factors.

5.4 ANALYSIS OF CHANGE IN Q_{MED}

It can be seen from Section 5.1.2, Section 5.2.2 & Section 5.3.2 that the Q_{med} value from the simulated discharge files increases with increasing urbanisation. This finding is nothing new and was already included in the original flood studies report. The Flood Studies Supplementary Report No 16 (FSSR 16 1985) suggested an amended version to include an urban fraction. More recently (Naden and Polarski 1990) have indicated that estimates of Q_{bar} made from rural catchment parameters should be increased by the factor $(1+URBEXT)^2$. This hypothesis has been tested on the Q_{med} values derived from the simulated runoff modelling undertaken in this study and the results are presented in Figure 5-16.

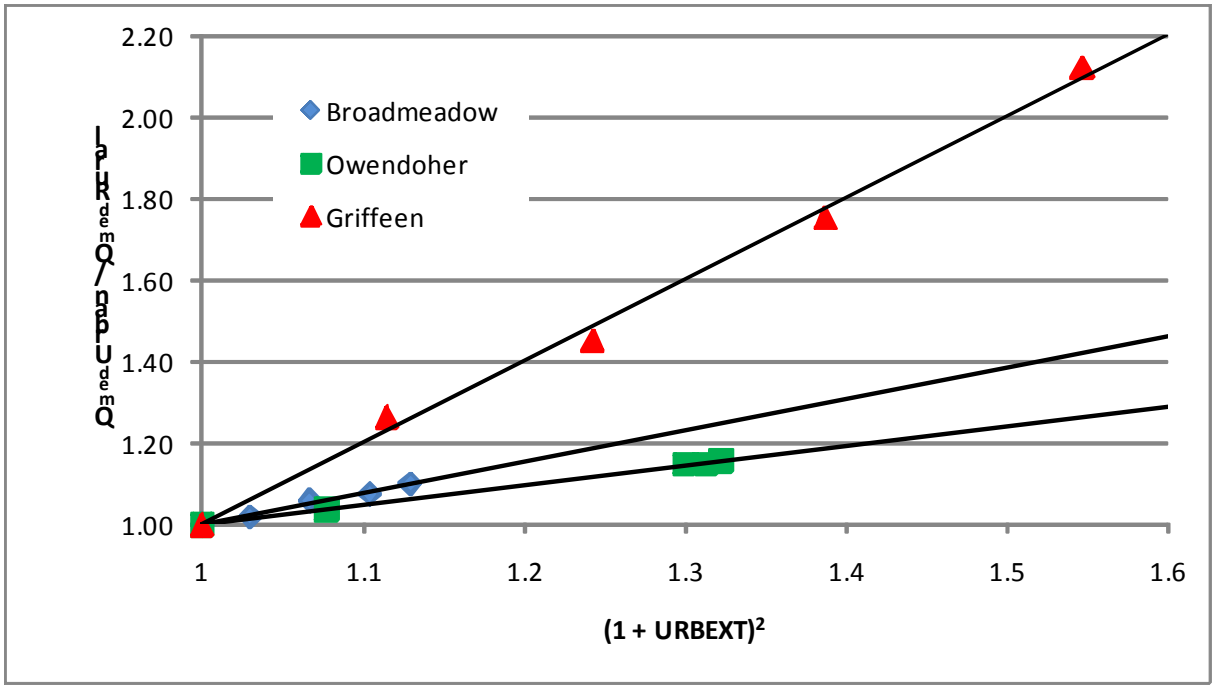


Figure 5-16 Correlation of Urban Extent with the ratio of rural to urbanised median flows

From the above diagram it can be seen that the correlation proposed by Naden and Polarski also holds in the case of the modelled Q_{med} flows derived from rainfall-runoff modelling as part of this study. It is important to note that whilst this relationship appears to hold true for the catchments investigated these are all located in the Greater Dublin area and as a consequence have broadly similar catchment permeability and climatic exposure. FSSR5 cited both catchment permeability and climatic setting of the catchment as being important modifying factors in the response of catchments to increasing urbanisation (the implication being that more permeable catchments are generally more susceptible to the effects of increasing urbanisation as are naturally drier areas). Thus the apparent relationship noted above may not be applicable to all catchments in Ireland.

6 CONCLUSIONS

Hydrometric Catchments

Approximately 32 hydrometric catchments were examined for possible use in this study and of this number only 3 were determined to meet the criteria required for the assessment of the impact of urbanisation on extreme runoff. This illustrates the difficulty involved in finding suitable highly urbanised catchments with corresponding well gauged river systems and high quality meteorological data in Ireland. Given the well documented rapid urban development seen in Ireland in the recent past this lack of suitable catchments is primarily due to limited availability of suitable hydrometric or high resolution meteorological data.

Analysis of Changes in Urbanisation Using Spatial Data

Recent changes to the extent of urbanisation within the three hydrometric gauge catchments selected for this study were identified by reference to aerial photography. The purpose of this task was to identify any significant changes in catchment urbanisation for comparison against changes in flow records at the gauging sites. The results of this analysis are presented in Table 2.2 in Section 2 of this document and reproduced here as Table 6.1.

	Gauge Catchments		
	Owendoher at Willbrook Road (Gauge No. 09009)	**Griffeen at Lucan (Gauge No. 09002)**	**Broadmeadow at Swords (Gauge No. 08008)**
Total Area (km^2)	22.6	35.0	108.0
Urban Fraction 1973	0.038	0.056	0.015
Urban Fraction 1995	0.140	0.115	0.033
Urban Fraction 2000	0.146	0.178	0.051
Urban Fraction 2008	0.150	0.244	0.063

Table 6.1 Changes in Urban Fraction 1973 - 2008

The principal change in urbanisation in the Owendoher catchment occurred between 1973 and 1995 with more moderate increases up to 2008. The increase in urbanisation of the Griffeen and the Broadmeadow catchments was more gradual between 1973 and 2008. In the Griffeen catchment the urbanised area has reached close to ¼ of the total catchment area while the Broadmeadow catchment remains relatively un-developed with only 6% of the total catchment being urbanised.

Analysis of Gauged Records

A trend analysis was undertaken on the gauged discharge records from the three chosen hydrometric gauging stations. The results of this analysis showed that no obvious trend towards increased extreme event frequency was observed in either the Owendoher or the Broadmeadow hydrometric data. A trend was identified in the Griffeen summer data but no trend was observed in the winter data for this gauge. The conclusions drawn from these results are as follows:

- The absence of an obvious trend in the Owendoher summer and winter data sets is attributed to the profile of the change in urbanisation over time. The major increase in urbanisation in this catchment occurred between 1973 and 1995 and equates to an increase of approximately 10% while between 1995 and 2008 there was only a marginal increase in urban area of approximately 1%. The gauged discharge data used in this analysis stretches from 1980 to 2007 and given the absence of an identifiable trend it is suggested that the large urban expansion most likely occurred prior to or shortly after 1980 i.e. before the start of the gauge records.

- The trend towards increased discharge with time, identified in the Griffeen summer data set is deemed to be due to the increased urbanisation seen in the Griffeen gauge catchment. The greater impermeable surface area associated with increased urbanisation creates larger peak run-off which results in increased discharge peaks in the Griffeen River. The lack of trend in the winter data-set can be attributed to antecedent soil conditions where the soil may be saturated much of the time during the winter months producing run-off conditions similar to those of an impermeable surface. Therefore the impact of increased urbanisation would be less obvious in the discharge records for the winter period.

- The large increase in event frequency shown in the final histogram bins in the Griffeen winter data-set may be attributable to the flood alleviation works carried out on the river channel in the vicinity of the gauging station site circa. 2004. Such an increase should also be seen in the summer season histograms and may be partially responsible for the increasing trend observed in this data.

- The absence of any obvious trend in the Broadmeadow summer and winter data sets is attributed to the relative size of the urbanised area to the overall catchment area. The urban areas within the Broadmeadow gauge catchment only accounts for approximately 6% of the overall catchment area and these areas are spread out throughout the catchment. The impact of the increased impermeable surface is therefore thought to be diluted by the larger greenfield run-off. In addition, the majority of the urban development is located at a distance from the gauging station site which increases the difficultly in identifying any discernable change in runoff response due to attenuation of the flood peaks through the river network.

A trend analysis was also carried out on rainfall records to identify whether the changes in the gauged discharge data can be attributed to trends in catchment rainfall. The results of this analysis show that there are no obvious trends towards increased frequency of extreme events in the rainfall data-sets for any of the three gauge catchments. Therefore any trend identified in gauged discharge cannot be exclusively attributed to changes in catchment rainfall.

Testing for Trend

A test for trend using cumulative analysis was applied to the gauged discharge data from the three gauge catchments. This method is often used in hydrology to identify changes in total or seasonal runoff and uses the number of events rather than the actual discharge values of the individual events. The conclusions drawn from this analysis are as follows:

- From analysis of the Owendoher gauge discharge data it was concluded that the number of summer season extreme events had in fact reduced despite increasing urbanisation while the number of winter season extreme events had remained relatively constant. However, the significant gaps in the Owendoher data set may have compromised this analysis

- The cumulative analysis of the Griffeen gauge discharge data confirmed that the number of extreme events for the summer season had significantly increased throughout the observation period. In recent years the number of extreme events in the winter season had, however, also increased, which could be attributed to a change in conveyance in the lower section of the

river due to the flood alleviations works undertaken in the vicinity of the gauging station site circa. 2004.

- The summer season extreme events in the Broadmeadow data set showed a significant variation from year to year, thus compromising the confidence in the results of this assessment. A simple best fit analysis indicated a non linear relationship with slightly decreasing slope toward the latter period of the observed data set, however as noted previously this cannot be said with reasonable confidence. For the Broadmeadow winter season extreme events the slope seemed to be decreasing thus indicating a reduction in extreme runoff events. From this analysis it was concluded that the number of extreme events overall had in fact slightly reduced despite increasing urbanisation.

Analysis of Simulated Discharge Data

Rainfall-runoff models were established for each of the three hydrometric gauge catchments examined in this study. These models were calibrated against gauged discharge data and then used to generate simulated discharge data using a long series of assimilated rainfall data. The simulated discharge data is composed of four separate discharge series for each gauge catchment, one for each of the estimated 1973, 1995, 2000 and 2008 urban extents. The analysis included a comparison of Annual Maxima flow series, Q_{med} estimates, Extreme Value Analysis (EVA) results and Growth Factor estimates. The conclusions drawn from this analysis are as follows:

- The peak discharges in the Annual Maxima Series for each of the three gauge catchments generally increase with increasing urbanisation. This agrees with the expected rainfall-runoff response.

- The Q_{med} value calculated from the Annual Maxima Series increases with increasing urbanisation. This agrees with the expected rainfall-runoff response.

- The results of the Griffeen and Broadmeadow analysis shows that the magnitude of the flows of known return period produced from the Extreme Value Analysis of the simulated discharge files increases with increasing urbanisation. Again, this agrees with the expected rainfall-runoff response.

Finally it has been shown that the increase in the modelled Q_{med} discharge derived from rainfall-runoff modelling in the Greater Dublin area is proportional to the value $(1 + URBEXT)^2$ in much the same manner that Naden & Polarski (1990) suggested for Q_{bar}. However due to the limited availability of suitably gauged and developed catchments it was not possible to test the impact of variations in the natural catchment permeability nor climatic setting of the catchment on this hypothesis, both of which have previously been identified (FSSR5) as potentially significant influences on catchment response to increasing urbanisation.

APPENDIX A

Griffeen at Lucan

Post-2004 Hydraulic Model Details

Griffeen at Lucan – Post-2004 Hydraulic Model Details

The weir and river channel at the hydrometric station on the River Griffeen at Lucan were altered as part of the flood alleviation works undertaken in the area in 2004. A hydraulic model was established for a length of the River Griffeen around the weir site using as-built survey drawings to produce a new rating curve to be applied to post 2004 measured water level data.

A model of approximately 280m of the River Griffeen was established using 11 surveyed channel cross-sections. The weir at the hydrometric gauging station was modelled as a hydraulic structure. **Figure A-1** presents a plan of the hydraulic model showing the cross-sections and weir locations.

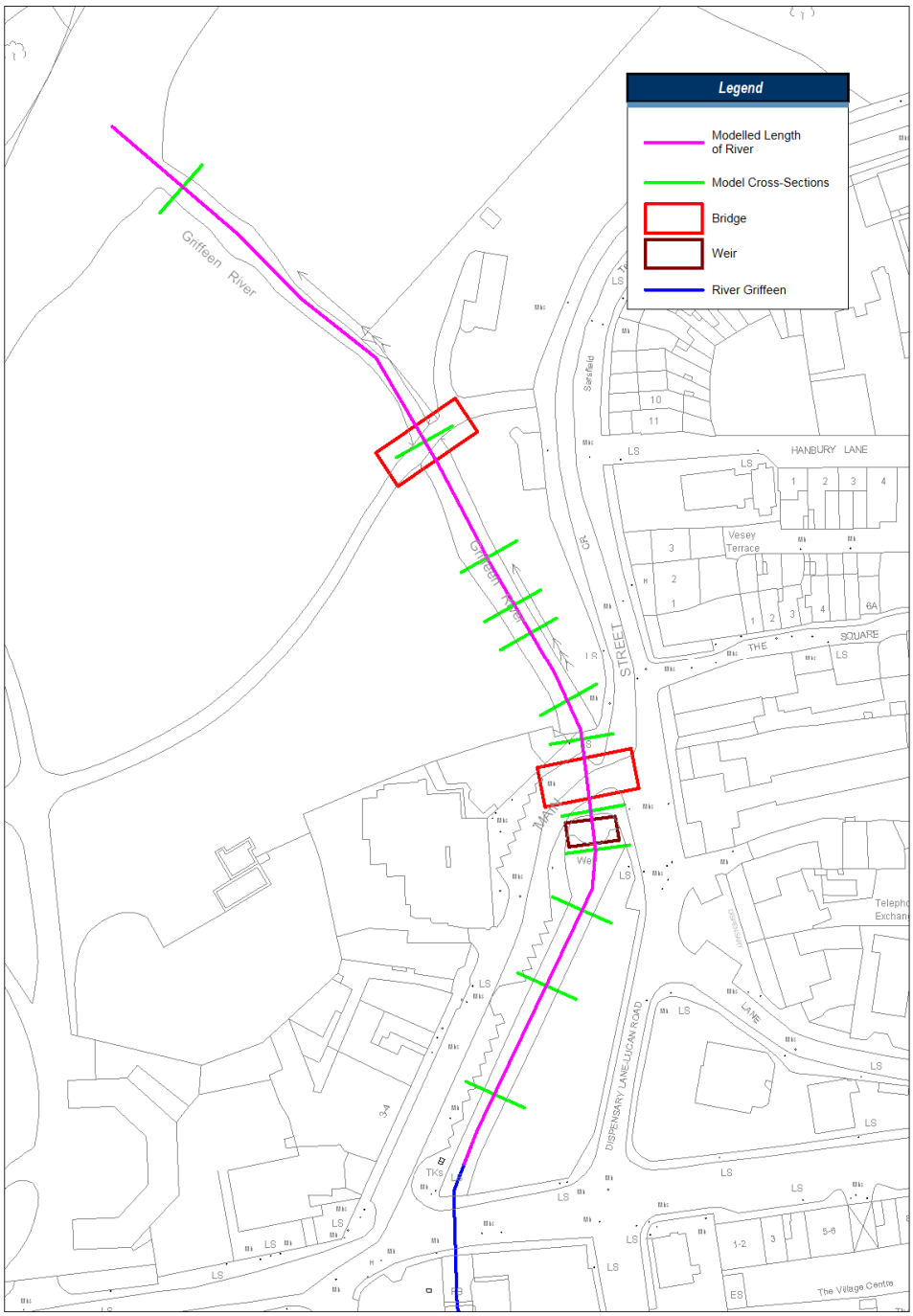


Figure A-1 Griffeen at Lucan Post-2004 Hydraulic Model Set-Up

Measured flow and water level data was provided by the OPW for the purposes of calibrating this model. A table of this data is presented here as **Table A-1**.

Date Measured	Water Level (mOD Poolbeg)	Flow (m^3/s)
31/08/2006	23.726	0.114
05/09/2006	23.732	0.163
12/10/2006	23.741	0.210
19/10/2006	23.796	0.592
02/02/2007	23.782	0.469
28/02/2007	23.845	0.961
26/11/2007	23.759	0.297
07/02/2008	23.796	0.593
22/07/2008	23.733	0.141
10/09/2008	23.820	0.830

Table A-1 Water Level and Flow Measured Used to Calibrate Hydraulic Model

Following calibration of the hydraulic model, a rating curve for the hydrometric gauge site was produced. This rating curve is presented as **Figure A-2**. A detailed portion of the rating curve is shown as **Figure A-3** along with the measured data from **Table A-1** demonstrating the satisfactory calibration of the model.

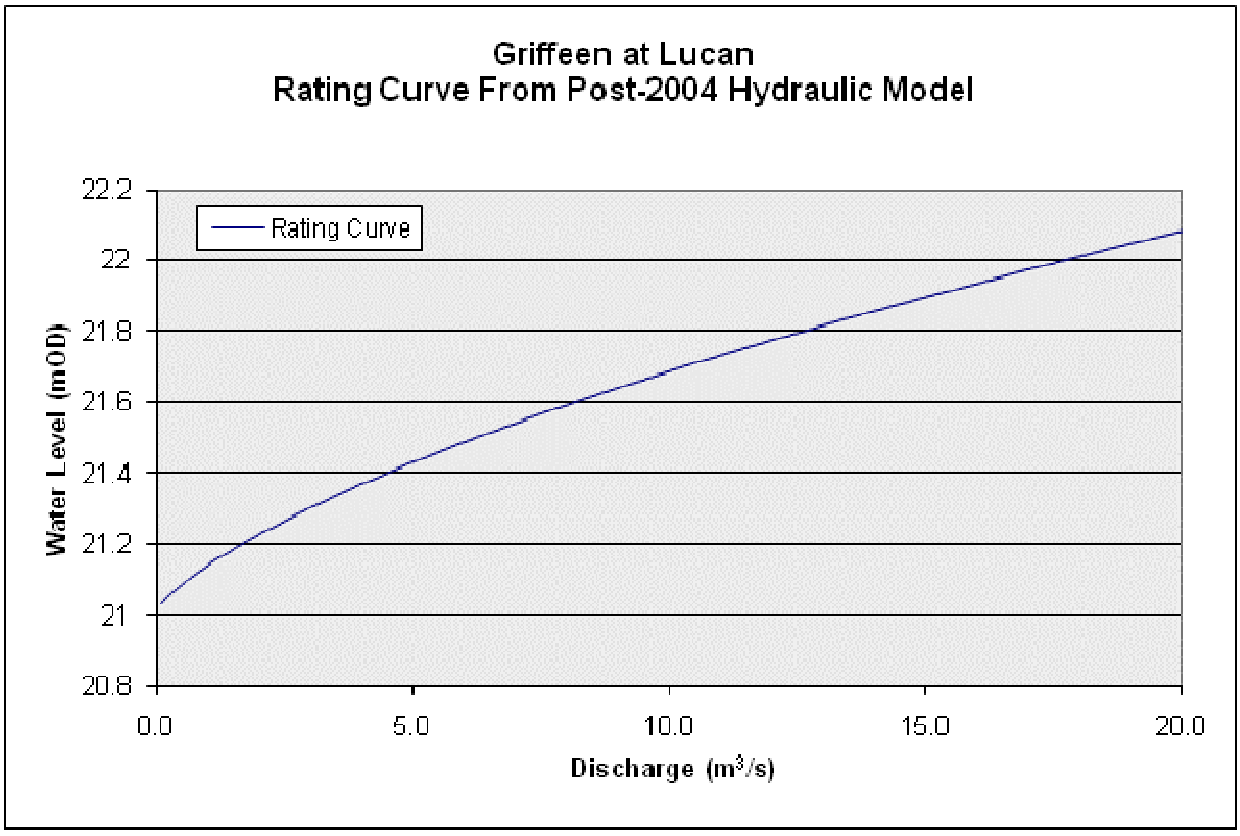


Figure A-2 Rating Curve from Griffeen at Lucan Post-2004 Hydraulic Model

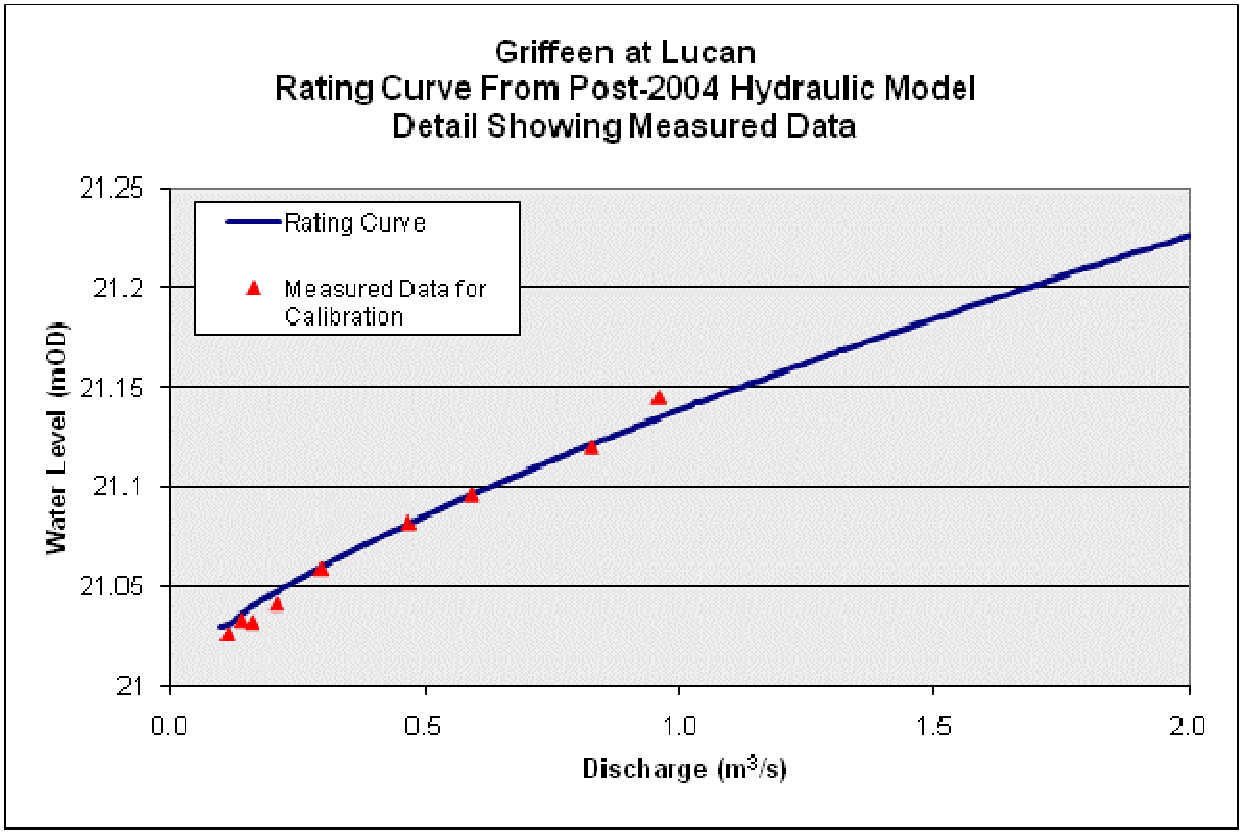
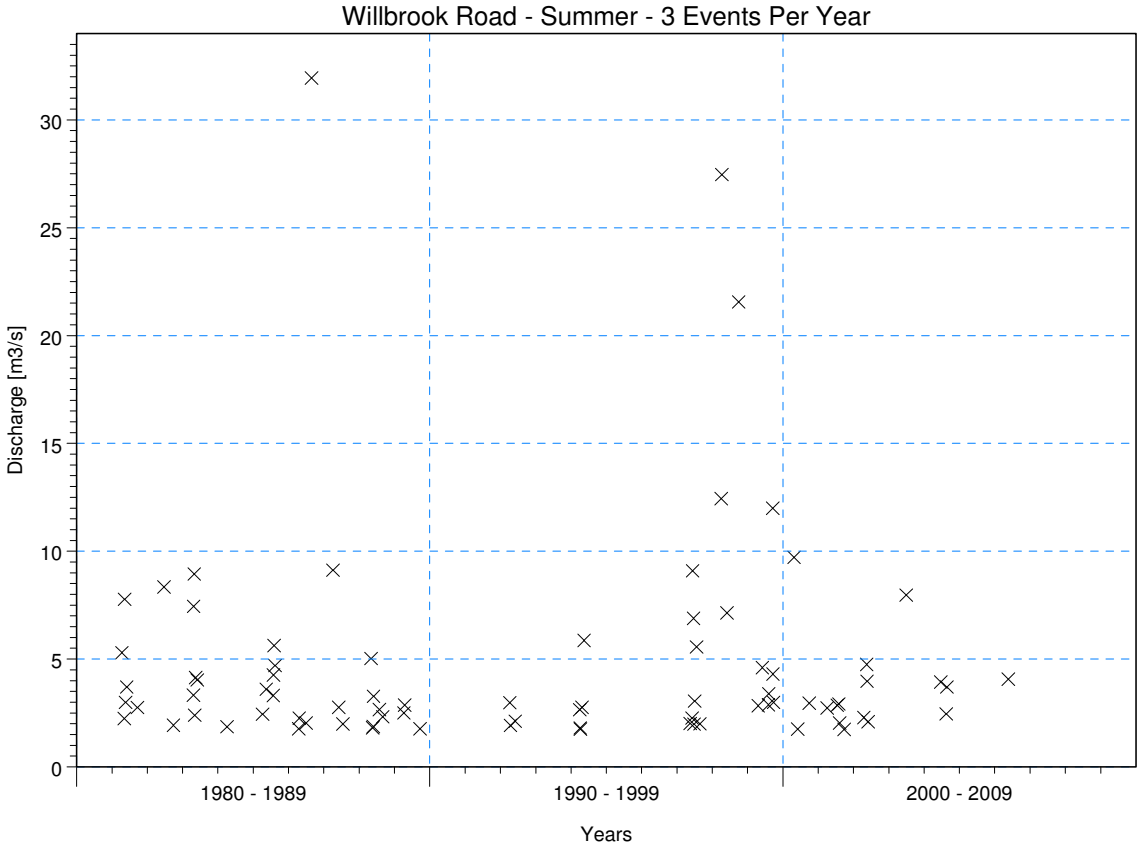
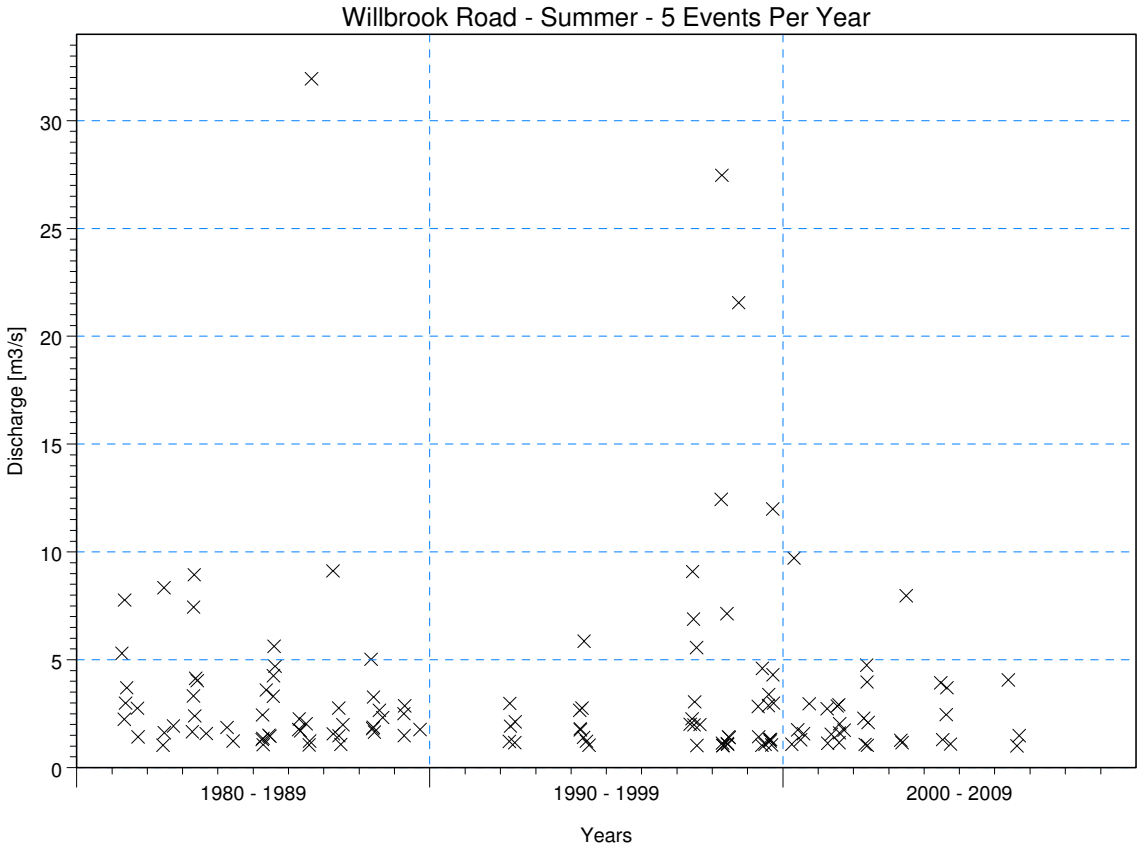


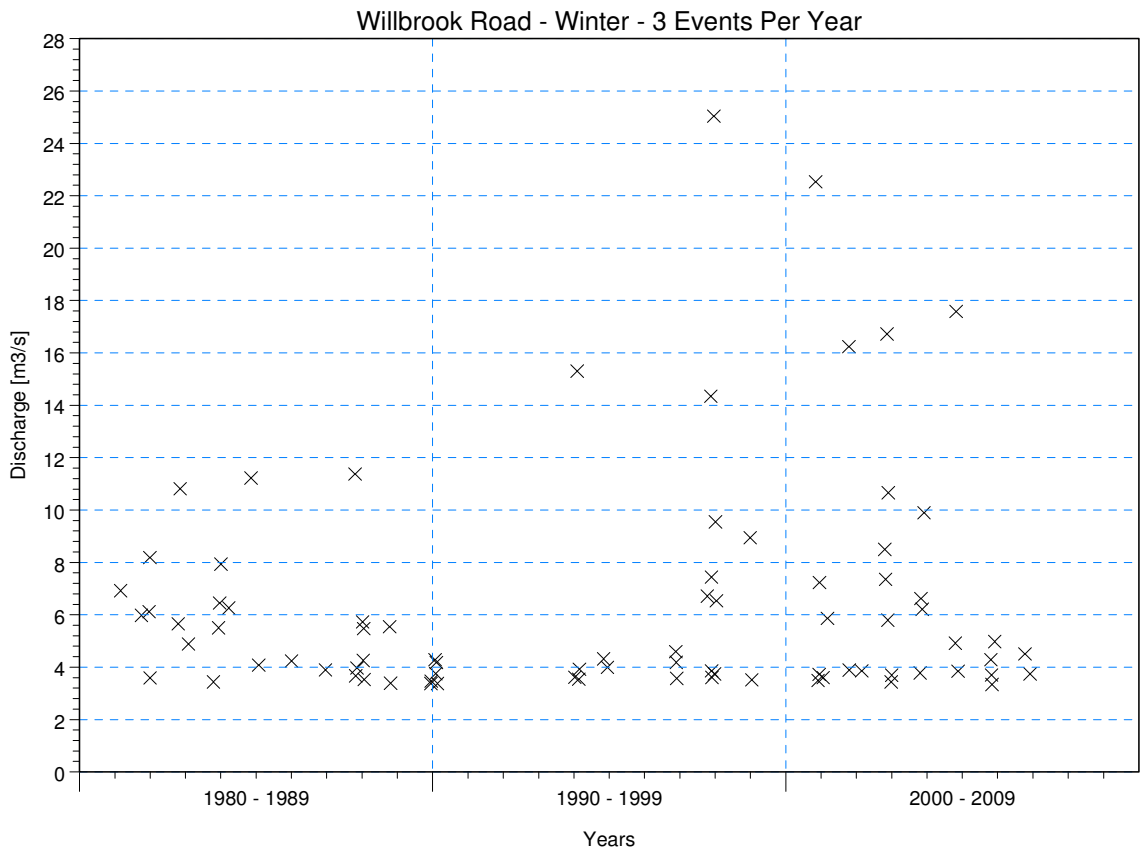
Figure A-3 Rating Curve Detail Showing Measured Data

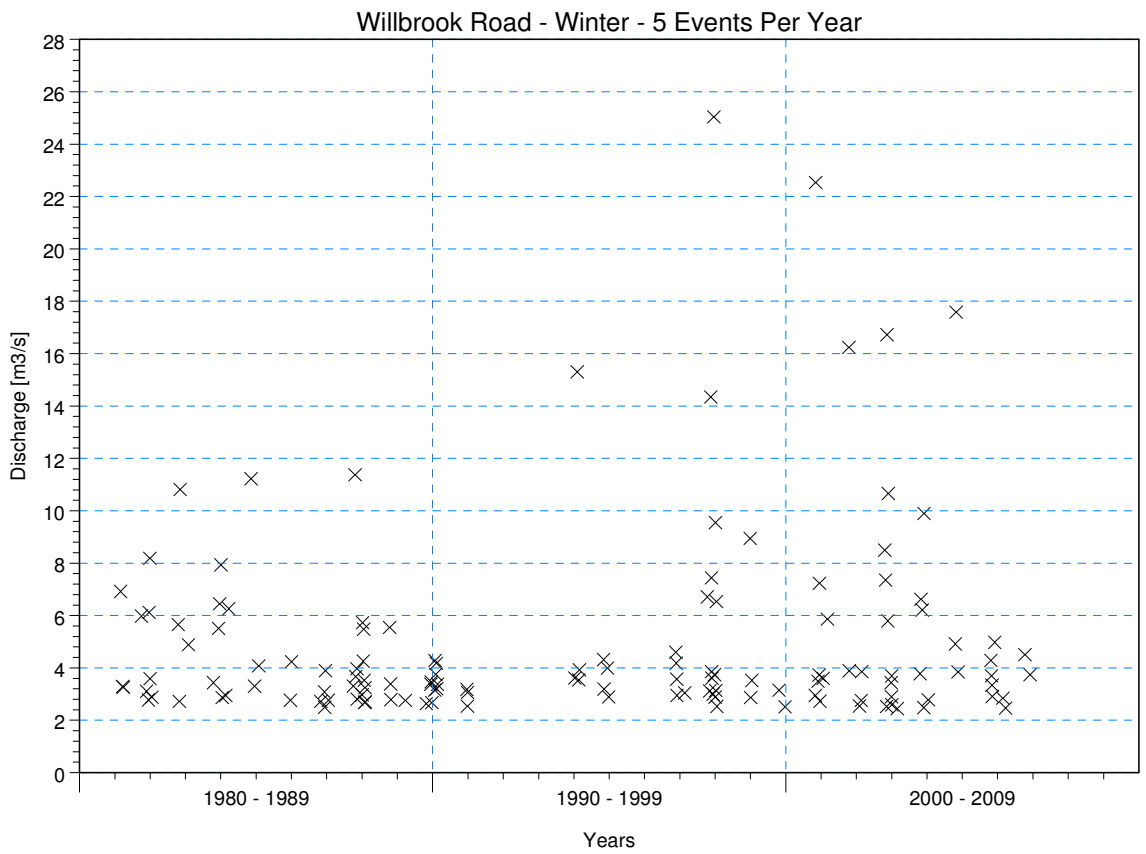
APPENDIX B

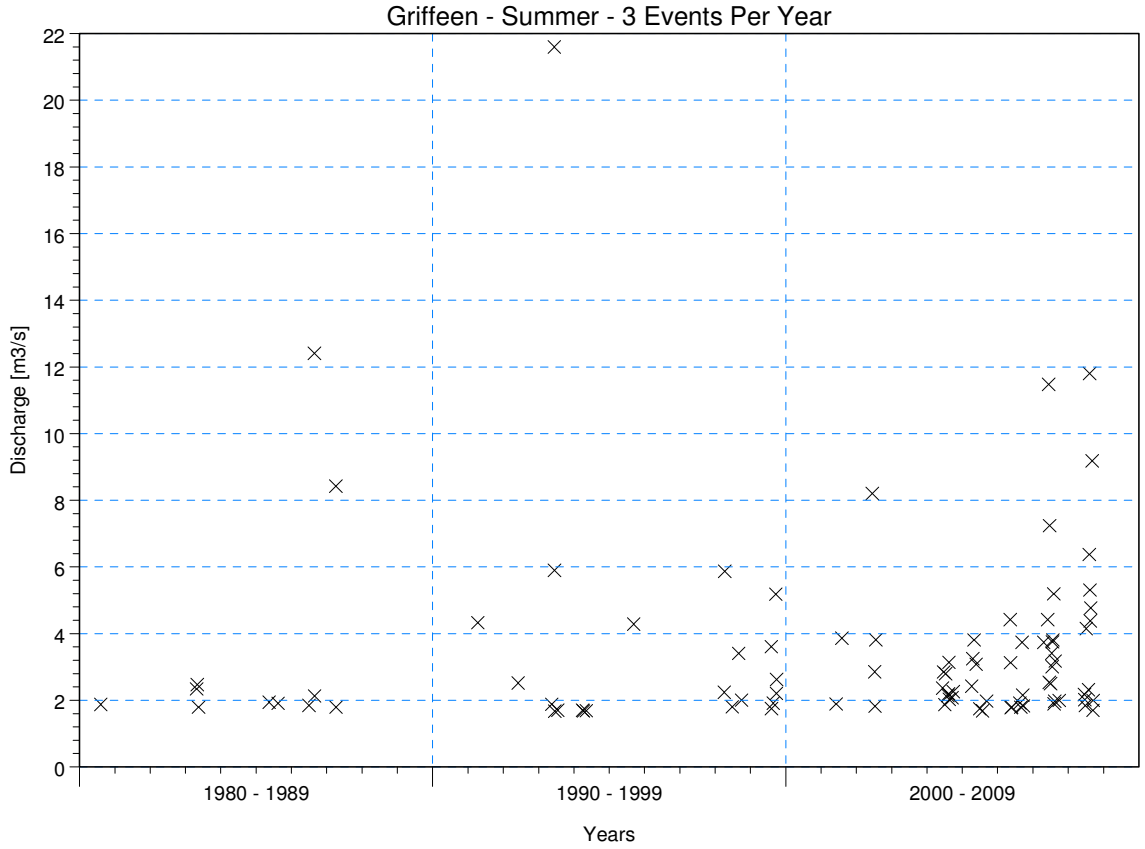
Peak Discharges from Gauged Events

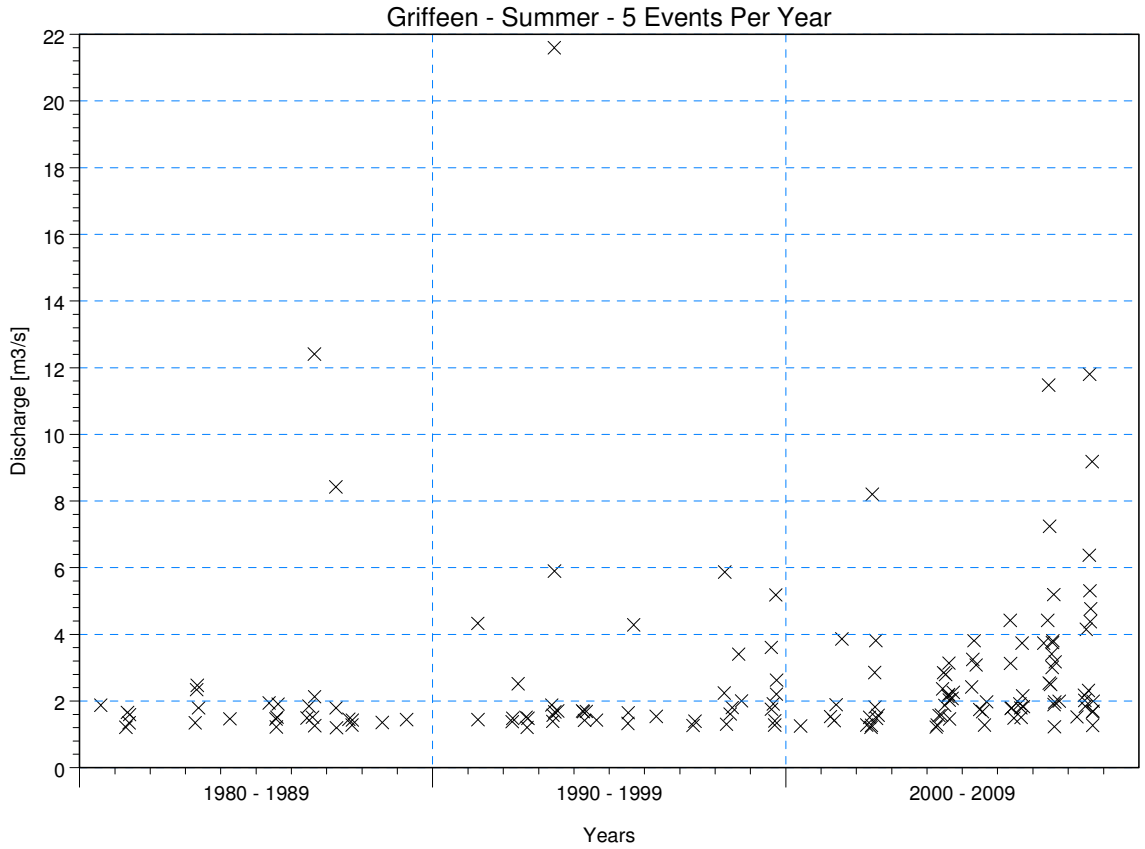

Willbrook Road - Summer - 3 Events Per Year
Discharge [m3/s]
0
5
10
15
20
25
30
1980 - 1989
1990 - 1999
2000 - 2009
Years

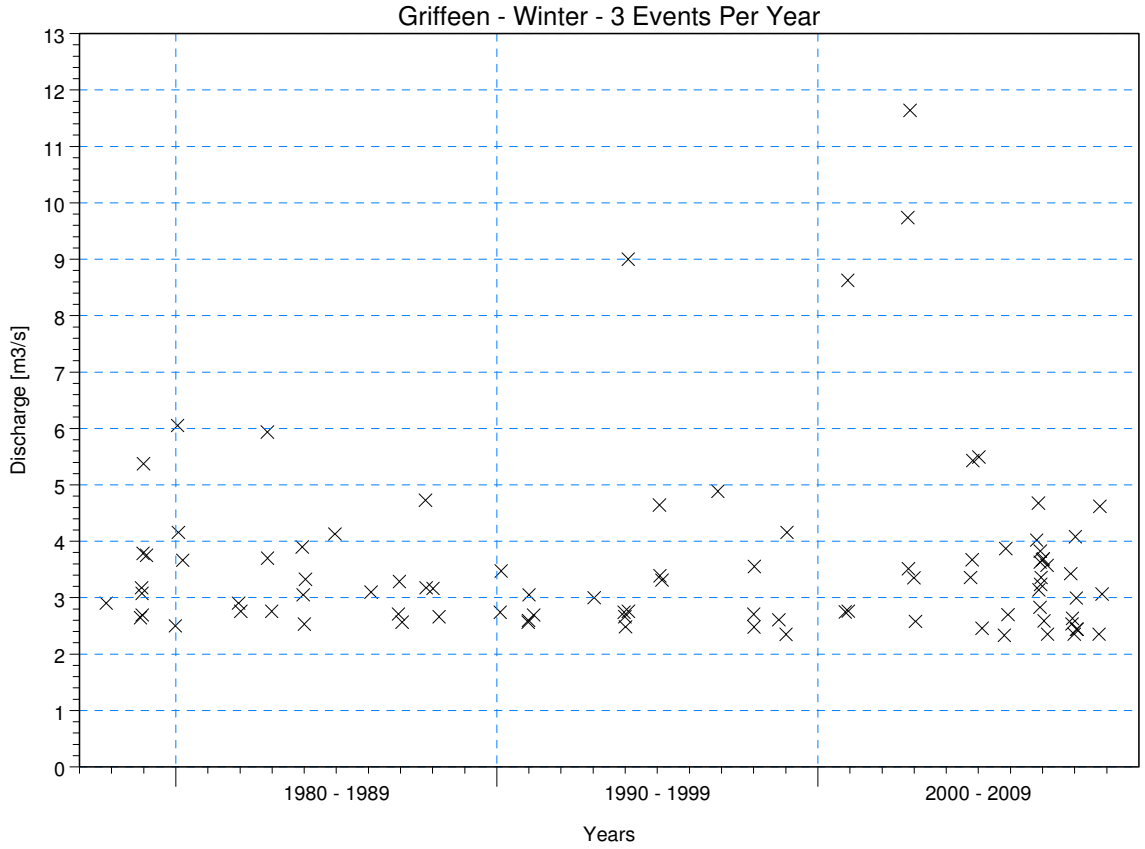

Willbrook Road - Summer - 5 Events Per Year
Discharge [m3/s]
0
5
10
15
20
25
30
1980 - 1989
1990 - 1999
2000 - 2009
Years

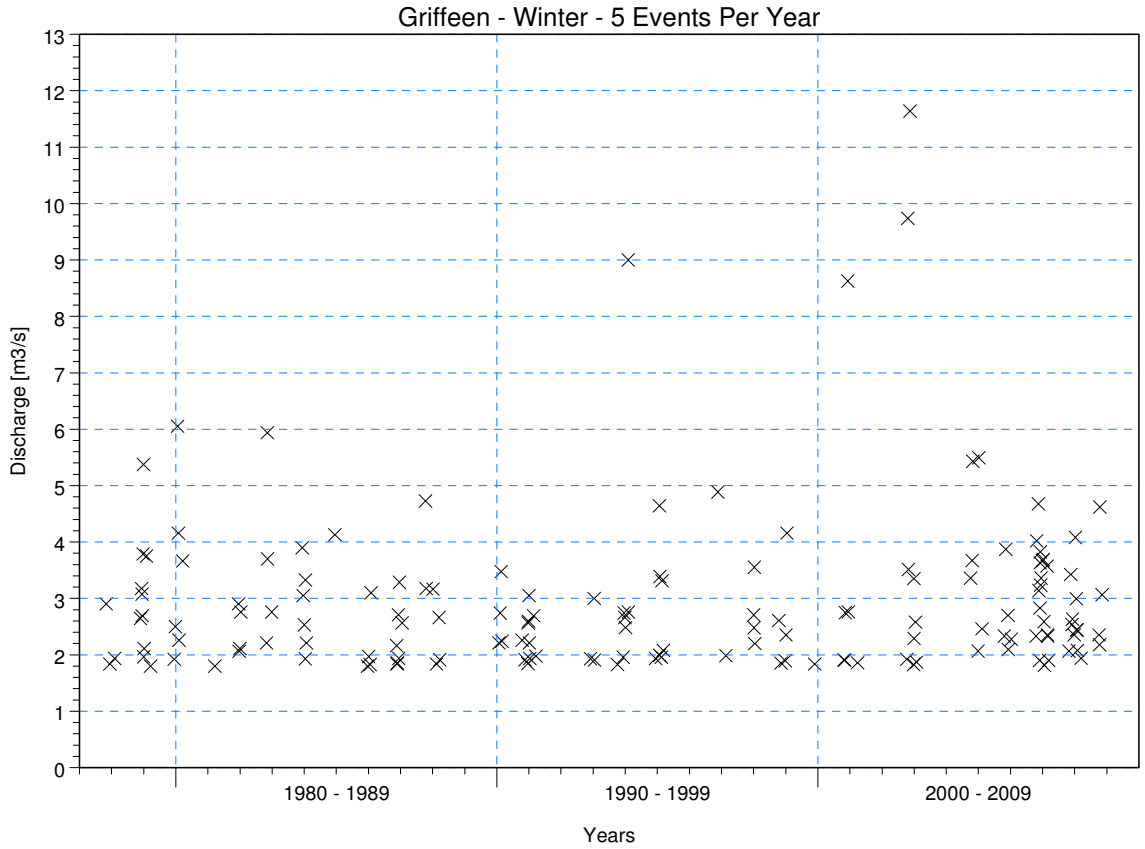

Willbrook Road - Winter - 3 Events Per Year
Discharge [m3/s]
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
1980 - 1989
1990 - 1999
2000 - 2009
Years

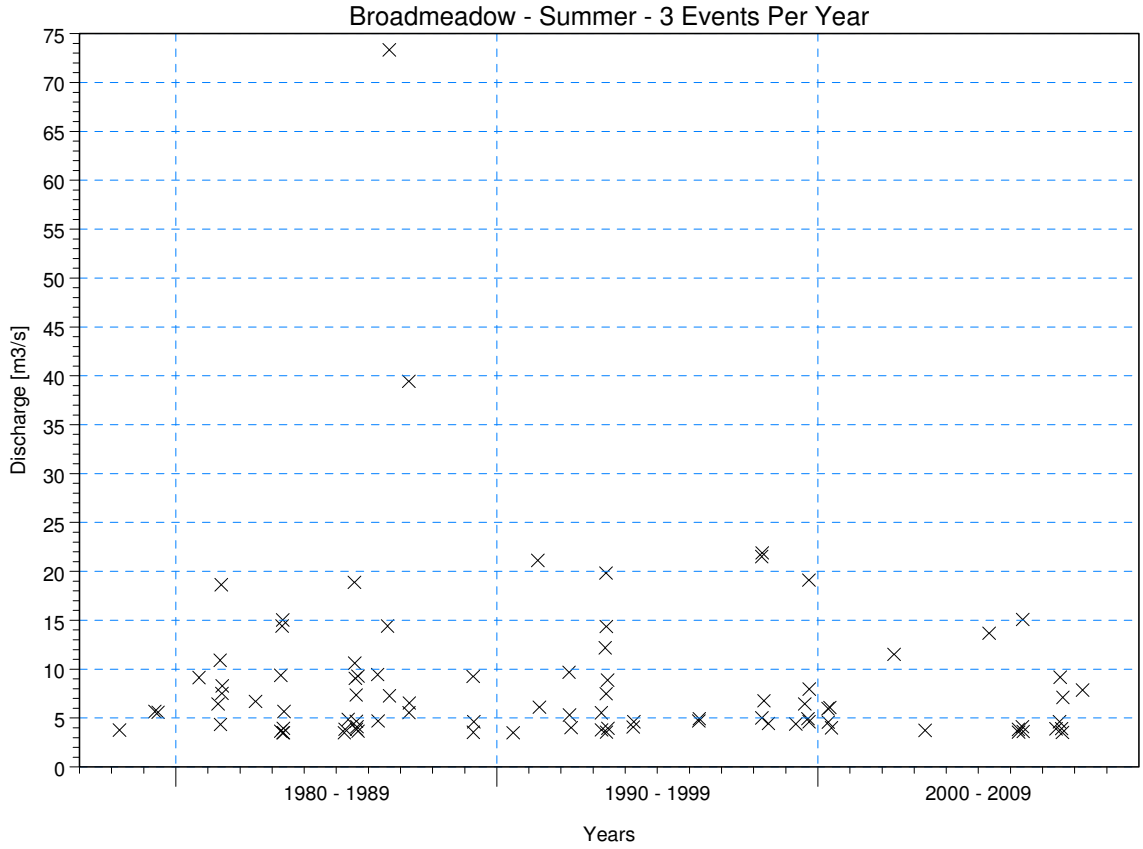

Willbrook Road - Winter - 5 Events Per Year
Discharge [m3/s]
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
1980 - 1989
1990 - 1999
2000 - 2009
Years

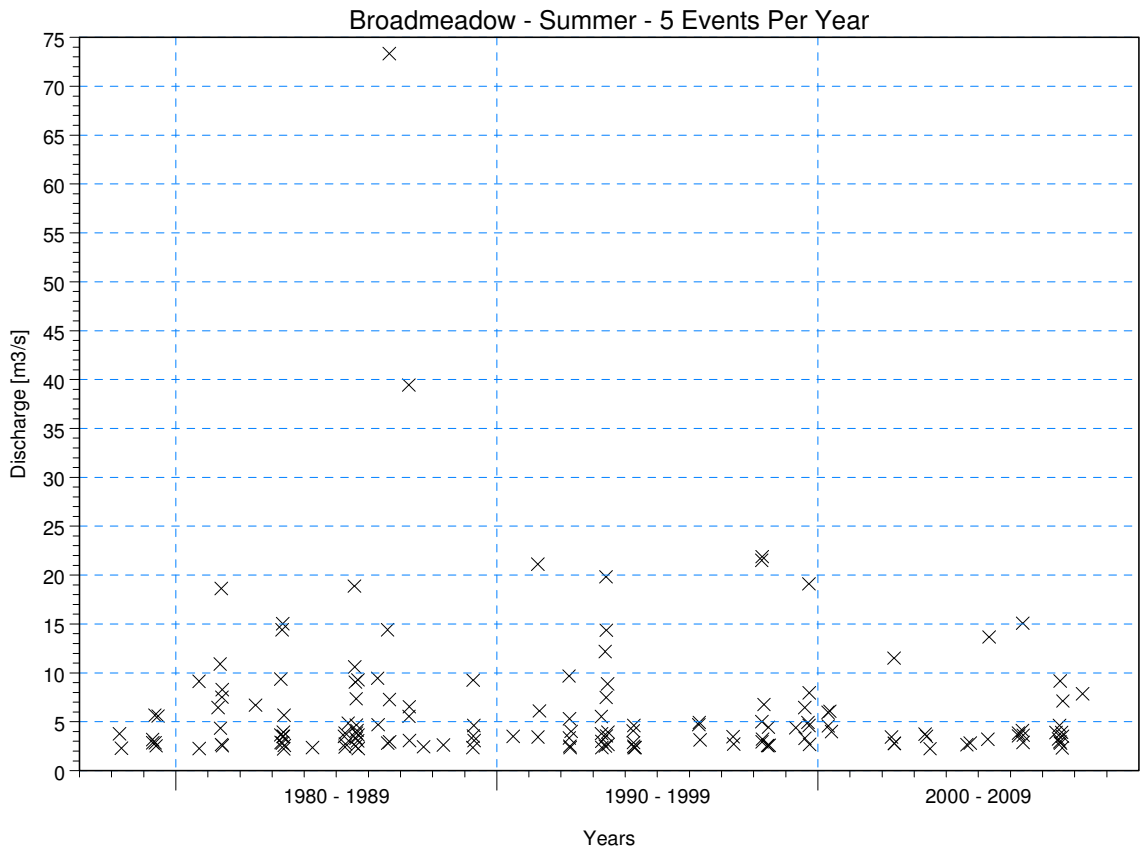

Griffeen - Summer - 3 Events Per Year
Discharge [m3/s]
0
2
4
6
8
10
12
14
16
18
20
22
1980 - 1989
1990 - 1999
2000 - 2009
Years

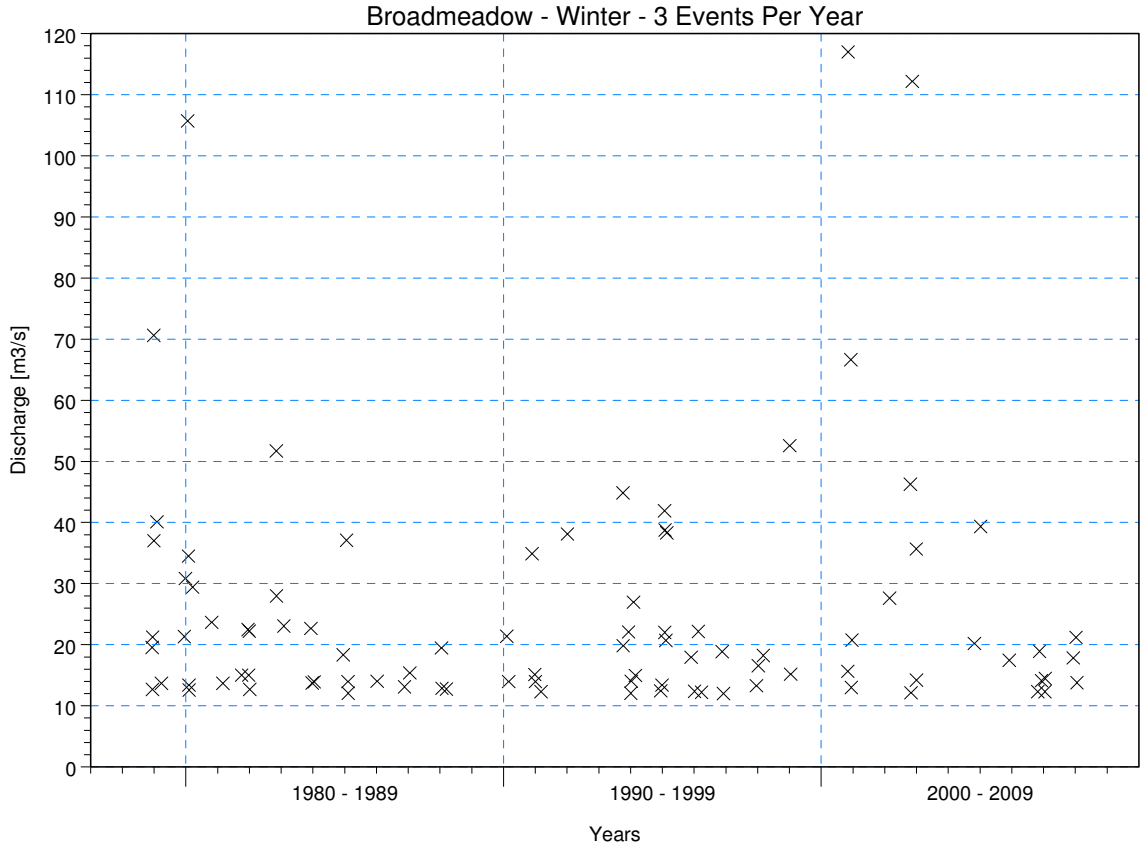

Griffeen - Summer - 5 Events Per Year
Discharge [m3/s]
0
2
4
6
8
10
12
14
16
18
20
22
1980 - 1989
1990 - 1999
2000 - 2009
Years

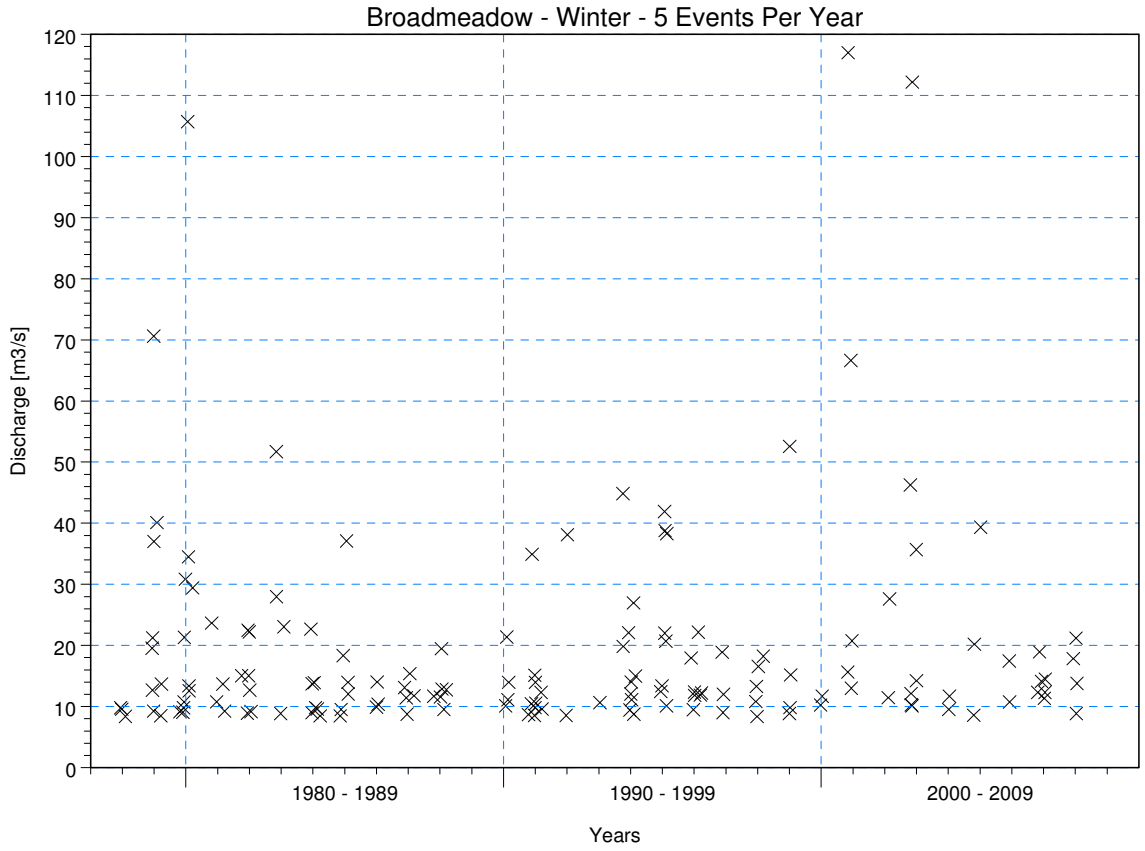

Griffeen - Winter - 3 Events Per Year
Discharge [m3/s]
0
1
2
3
4
5
6
7
8
9
10
11
12
13
1980 - 1989
1990 - 1999
2000 - 2009
Years


Griffeen - Winter - 5 Events Per Year
Discharge [m3/s]
0
1
2
3
4
5
6
7
8
9
10
11
12
13
1980 - 1989
1990 - 1999
2000 - 2009
Years


Broadmeadow - Summer - 3 Events Per Year
Discharge [m3/s]
0
5
10
15
20
25
30
35
40
45
50
55
60
65
70
75
1980 - 1989
1990 - 1999
2000 - 2009
Years


Broadmeadow - Summer - 5 Events Per Year
Discharge [m3/s]
0
5
10
15
20
25
30
35
40
45
50
55
60
65
70
75
1980 - 1989
1990 - 1999
2000 - 2009
Years


Broadmeadow - Winter - 3 Events Per Year
Discharge [m3/s]
0
10
20
30
40
50
60
70
80
90
100
110
120
1980 - 1989
1990 - 1999
2000 - 2009
Years


Broadmeadow - Winter - 5 Events Per Year
Discharge [m3/s]
0
10
20
30
40
50
60
70
80
90
100
110
120
1980 - 1989
1990 - 1999
2000 - 2009
Years

APPENDIX C

Annual Maxima Series from Simulated Data Sets

Owendoher at Willbrook Road (Gauge No. 09009)			
1973 Urban Extent		1995 Urban Extent	
Date	Flow (m^3/s)	Date	Flow (m^3/s)
27/12/1964 10:30	7.39	27/12/1964 10:15	7.45
17/11/1965 20:15	19.03	17/11/1965 20:15	19.59
22/02/1967 22:00	18.64	22/02/1967 22:00	19.81
09/01/1968 01:00	6.29	02/11/1968 04:15	7.33
22/02/1969 10:00	13.91	22/02/1969 10:00	13.96
25/04/1970 03:30	7.38	25/04/1970 03:15	7.45
20/01/1971 22:15	9.79	20/01/1971 22:00	11.94
02/02/1972 09:15	15.66	02/02/1972 09:15	14.36
19/01/1973 17:30	9.59	19/01/1973 17:45	10.17
01/02/1974 09:15	14.26	01/02/1974 09:15	13.98
25/01/1975 07:00	5.68	25/01/1975 07:00	6.18
30/12/1976 05:15	7.31	30/12/1976 05:15	7.56
24/02/1977 17:00	10.40	24/02/1977 17:00	10.18
23/12/1978 19:00	19.17	23/12/1978 19:00	20.75
14/12/1979 22:15	9.33	14/12/1979 22:15	10.31
21/01/1980 05:00	16.23	21/01/1980 05:00	17.88
13/04/1981 04:15	9.48	13/04/1981 04:15	9.72
06/11/1982 12:15	6.83	16/01/1982 17:00	15.39
25/04/1983 09:00	11.28	25/04/1983 09:00	11.52
25/03/1984 08:30	9.96	25/03/1984 08:30	10.32
04/03/1985 04:15	4.65	04/08/1985 15:15	5.74
26/08/1986 00:00	6.08	26/08/1986 00:00	10.02
21/10/1987 04:15	7.03	21/10/1987 04:15	10.92
18/01/1988 23:30	6.01	18/01/1988 23:30	6.27
06/04/1989 09:45	2.29	27/10/1989 03:59	3.21
28/12/1990 13:14	4.35	01/02/1990 15:59	5.29
12/04/1991 12:14	11.14	12/04/1991 12:14	12.19
31/03/1992 02:44	3.18	31/03/1992 02:29	3.99
11/06/1993 20:59	8.94	11/06/1993 20:59	11.54
03/02/1994 08:14	20.43	03/02/1994 08:14	20.42
10/03/1995 09:15	11.69	10/03/1995 09:15	13.57
09/02/1996 07:14	8.46	19/11/1996 08:59	11.30
18/12/1997 08:59	9.34	18/12/1997 08:59	11.10
09/04/1998 04:59	12.61	09/04/1998 04:59	13.36
15/01/1999 17:14	5.19	05/11/1999 05:59	5.47
08/12/2000 01:14	11.38	08/12/2000 01:14	12.79
17/05/2001 02:14	3.86	17/05/2001 01:59	4.50
27/12/2002 05:44	9.75	15/11/2002 02:14	10.05
02/12/2003 08:14	9.42	02/12/2003 08:14	9.37
27/10/2004 17:14	4.33	21/06/2004 13:14	10.60
12/02/2005 03:29	5.02	02/12/2005 05:14	5.61
29/12/2006 08:30	2.94	15/11/2006 08:59	5.17
03/03/2007 17:30	5.81	03/03/2007 17:30	6.88

Table C-1 – Owendoher Annual Maxima Series of Simulated Discharge – Table 1

Owendoher at Willbrook Road (Gauge No. 09009)			
2000 Urban Extent		2008 Urban Extent	
Date	Flow (m^3/s)	Date	Flow (m^3/s)
27/12/1964 10:15	7.45	27/12/1964 10:30	5.61
17/11/1965 20:15	19.63	17/11/1965 20:15	19.36
22/02/1967 22:00	19.88	22/02/1967 22:00	19.92
02/11/1968 04:15	7.52	02/11/1968 04:15	7.66
22/02/1969 10:15	13.97	22/02/1969 10:15	13.97
25/04/1970 03:15	7.46	25/04/1970 03:15	7.46
20/01/1971 22:00	12.07	20/01/1971 22:00	12.15
02/02/1972 09:15	14.30	02/02/1972 09:15	14.24
19/01/1973 17:45	10.21	19/01/1973 17:45	10.23
01/02/1974 09:15	13.97	01/02/1974 09:15	13.95
25/01/1975 07:00	6.21	25/01/1975 07:00	6.23
30/12/1976 05:15	7.58	30/12/1976 05:15	7.58
24/02/1977 17:00	10.17	24/02/1977 17:00	10.16
23/12/1978 19:00	20.84	23/12/1978 19:00	20.90
14/12/1979 22:15	10.37	14/12/1979 22:15	10.41
21/01/1980 05:00	17.98	21/01/1980 05:00	18.04
13/04/1981 04:15	9.74	13/04/1981 04:15	9.74
16/01/1982 17:00	15.98	16/01/1982 17:00	16.40
25/04/1983 09:00	11.53	25/04/1983 09:00	11.54
25/03/1984 08:30	10.34	25/03/1984 08:30	10.35
04/08/1985 15:15	5.90	04/08/1985 15:15	6.02
26/08/1986 00:00	10.24	26/08/1986 00:00	10.40
21/10/1987 04:15	11.14	21/10/1987 04:15	11.29
18/01/1988 23:30	6.29	18/01/1988 23:30	6.29
27/10/1989 03:59	3.33	27/10/1989 03:59	3.42
01/02/1990 15:59	5.36	01/02/1990 15:59	5.40
12/04/1991 12:14	12.26	12/04/1991 12:14	12.30
31/03/1992 02:29	4.03	31/03/1992 02:29	4.07
11/06/1993 20:59	11.68	11/06/1993 20:59	11.78
03/02/1994 08:14	20.43	03/02/1994 08:14	20.42
10/03/1995 09:15	13.68	10/03/1995 09:15	13.75
19/11/1996 08:59	11.48	19/11/1996 08:59	11.61
18/12/1997 08:59	11.20	18/12/1997 08:59	11.27
09/04/1998 04:59	13.40	09/04/1998 04:59	13.43
05/11/1999 05:59	5.52	05/11/1999 05:59	5.56
08/12/2000 01:14	12.87	08/12/2000 01:14	12.92
17/05/2001 01:59	4.54	17/05/2001 01:59	4.56
15/11/2002 02:14	10.15	15/11/2002 02:14	10.22
02/12/2003 08:14	9.37	02/12/2003 08:14	9.36
21/06/2004 13:14	11.03	21/06/2004 13:14	11.33
02/12/2005 05:14	5.67	02/12/2005 05:14	5.71
15/11/2006 08:59	5.32	15/11/2006 08:59	5.42
03/03/2007 17:30	6.94	03/03/2007 17:30	6.98

Table C-2 – Owendoher Annual Maxima Series of Simulated Discharge – Table 2

Griffeen at Lucan (Gauge No. 09002)			
1973 Urban Extent		1995 Urban Extent	
Date	Flow (m^3/s)	Date	Flow (m^3/s)
24/03/1964 23:00	2.00	24/03/1964 20:15	2.17
27/12/1964 14:00	2.94	10/10/1964 08:15	3.45
17/11/1965 21:00	6.63	17/11/1965 20:30	7.63
23/02/1967 01:15	8.74	23/02/1967 01:00	9.36
17/10/1967 03:30	3.92	17/10/1967 02:00	4.65
02/11/1968 08:00	7.45	02/11/1968 07:15	8.71
25/04/1970 10:15	2.95	25/04/1970 08:30	3.26
19/03/1971 04:00	3.35	19/03/1971 03:15	3.66
19/01/1972 05:45	2.99	19/01/1972 03:15	3.25
12/11/1972 21:15	2.06	16/07/1973 02:15	2.87
08/01/1974 17:30	2.90	08/01/1974 15:30	3.10
25/01/1975 12:15	3.38	25/01/1975 10:15	3.66
27/09/1976 17:15	2.68	25/09/1976 04:15	3.62
24/02/1977 21:00	3.41	24/02/1977 20:15	3.51
31/10/1977 06:15	4.72	31/10/1977 06:15	5.60
01/02/1979 17:15	4.27	01/02/1979 16:15	4.47
31/01/1980 12:15	4.80	31/01/1980 12:15	5.24
22/03/1981 03:30	2.21	22/03/1981 02:00	2.40
23/11/1981 13:00	2.45	22/06/1982 16:00	3.11
06/11/1982 16:00	6.38	06/11/1982 14:15	7.12
09/12/1983 10:30	4.50	09/12/1983 10:00	5.33
14/12/1984 22:15	5.60	14/12/1984 22:00	5.95
26/08/1986 02:00	8.75	26/08/1986 01:15	10.67
05/04/1987 04:15	6.15	05/04/1987 04:00	6.63
21/10/1987 08:00	4.37	21/10/1987 07:00	5.41
22/09/1989 18:15	1.94	22/09/1989 17:15	2.93
19/02/1990 22:15	3.34	19/02/1990 20:30	3.48
12/04/1991 16:15	4.02	16/10/1990 01:15	4.36
31/10/1991 15:15	2.51	31/10/1991 10:00	3.21
11/06/1993 23:15	16.89	11/06/1993 23:15	18.89
03/02/1994 23:15	5.79	03/02/1994 23:15	6.25
25/01/1995 22:30	4.93	25/01/1995 22:00	5.51
29/11/1995 11:45	3.34	29/11/1995 10:15	3.98
19/11/1996 16:00	9.50	19/11/1996 15:15	10.47
09/04/1998 10:15	6.58	09/04/1998 10:00	7.14
20/09/1999 21:15	4.85	20/09/1999 19:15	5.94
12/01/2000 18:15	2.90	12/01/2000 17:30	3.01
06/11/2000 03:00	12.42	06/11/2000 00:15	13.77
26/02/2002 08:00	3.08	26/02/2002 06:00	3.25
15/11/2002 03:15	10.29	15/11/2002 03:15	11.25
23/10/2003 06:15	3.13	23/10/2003 06:00	3.75
28/10/2004 04:00	5.12	28/10/2004 02:45	5.67
03/12/2005 07:15	2.34	03/12/2005 07:00	2.53
05/08/2007 16:15	3.90	05/08/2007 14:15	4.71
05/09/2008 15:30	7.07	05/09/2008 14:30	8.22
14/10/2008 19:00	2.65	14/10/2008 18:00	2.83

Table C-3 – Griffeen Annual Maxima Series of Simulated Discharge – Table 1

Griffeen at Lucan (Gauge No. 09002)			
2000 Urban Extent		2008 Urban Extent	
Date	Flow (m^3/s)	Date	Flow (m^3/s)
24/03/1964 20:15	2.47	15/08/1964 20:00	2.87
10/10/1964 08:15	4.33	10/10/1964 08:00	5.29
17/11/1965 20:15	8.81	17/11/1965 20:15	10.09
23/02/1967 00:30	10.04	22/02/1967 23:15	10.93
17/10/1967 01:15	5.55	17/10/1967 01:15	6.58
02/11/1968 07:15	10.14	02/11/1968 07:00	11.71
25/04/1970 08:15	3.71	25/04/1970 08:15	4.19
19/03/1971 03:15	4.00	24/07/1971 04:15	4.54
19/01/1972 02:15	3.75	19/01/1972 02:15	4.34
16/07/1973 02:15	3.94	16/07/1973 02:15	5.07
08/01/1974 13:15	3.58	08/01/1974 13:15	4.23
25/01/1975 09:15	4.10	25/01/1975 09:15	4.65
25/09/1976 04:15	4.97	25/09/1976 04:15	6.41
24/08/1977 13:15	5.04	24/08/1977 13:15	6.85
31/10/1977 04:15	6.73	31/10/1977 04:00	8.13
01/02/1979 16:15	4.73	01/02/1979 16:15	5.00
21/01/1980 10:15	5.76	07/08/1980 10:00	7.24
22/03/1981 00:15	2.70	22/03/1981 00:00	3.10
22/06/1982 15:00	4.34	22/06/1982 14:15	5.76
06/11/1982 14:15	7.97	06/11/1982 14:15	8.86
09/12/1983 09:15	6.27	09/12/1983 09:15	7.39
14/12/1984 22:00	6.32	14/12/1984 22:00	6.71
26/08/1986 01:00	12.84	26/08/1986 01:00	15.21
05/04/1987 03:15	7.19	05/04/1987 03:00	7.80
21/10/1987 06:15	6.72	21/10/1987 06:15	8.16
22/09/1989 17:15	4.06	22/09/1989 17:15	5.25
19/02/1990 19:15	3.82	19/02/1990 19:15	4.23
16/10/1990 01:15	5.46	16/10/1990 01:00	6.63
31/10/1991 09:15	4.07	31/10/1991 09:15	4.97
11/06/1993 23:15	20.99	11/06/1993 23:00	23.26
03/02/1994 23:15	6.72	03/02/1994 23:00	7.25
25/01/1995 21:15	6.29	25/01/1995 21:15	7.16
29/11/1995 10:00	4.71	29/11/1995 10:00	5.51
19/11/1996 13:30	11.57	19/11/1996 13:15	13.17
09/04/1998 10:00	7.76	09/04/1998 09:15	8.48
20/09/1999 19:15	7.37	20/09/1999 19:15	8.87
12/01/2000 17:15	3.16	05/11/1999 06:15	3.51
06/11/2000 00:00	15.52	05/11/2000 23:15	17.54
26/02/2002 05:00	3.63	07/10/2001 22:00	4.29
15/11/2002 03:00	12.25	15/11/2002 03:00	13.39
23/10/2003 02:15	4.52	22/10/2003 15:00	5.57
20/10/2004 23:15	6.73	20/10/2004 23:15	8.41
03/12/2005 07:00	2.73	24/10/2005 02:15	2.97
05/08/2007 14:00	5.66	05/08/2007 14:00	6.71
05/09/2008 14:15	9.77	05/09/2008 14:00	11.45
14/10/2008 14:15	3.32	14/10/2008 14:00	3.91

Table C-4 – Griffeen Annual Maxima Series of Simulated Discharge – Table 2

Broadmeadow at Swords (Gauge No. 08008)			
1973 Urban Extent		1995 Urban Extent	
Date	Flow (m^3/s)	Date	Flow (m^3/s)
19/03/1964 20:30	17.07	19/03/1964 20:30	17.15
20/01/1965 10:15	36.06	20/01/1965 10:15	36.16
25/11/1965 11:30	52.53	25/11/1965 11:30	52.84
23/02/1967 01:15	39.59	23/02/1967 01:15	39.57
09/01/1968 03:00	33.24	09/01/1968 03:00	33.32
24/12/1968 20:15	52.06	24/12/1968 20:15	52.08
21/12/1969 03:15	9.18	21/12/1969 03:00	9.23
19/03/1971 04:30	38.99	19/03/1971 04:30	39.10
16/01/1972 02:45	11.39	16/01/1972 02:45	11.43
28/12/1972 17:15	24.10	28/12/1972 17:15	24.45
24/12/1973 02:00	18.70	24/12/1973 02:00	18.82
25/01/1975 10:45	20.48	25/01/1975 10:45	20.62
09/01/1976 11:00	12.93	09/01/1976 10:45	13.04
10/02/1977 19:15	21.31	10/02/1977 19:15	21.31
01/03/1978 16:00	9.62	01/03/1978 16:00	9.61
01/02/1979 12:45	40.98	01/02/1979 12:45	40.96
21/01/1980 12:30	46.75	21/01/1980 12:30	46.78
01/03/1981 21:30	16.88	01/03/1981 21:30	16.93
13/12/1981 21:15	34.44	13/12/1981 21:00	34.71
06/11/1982 15:15	58.13	06/11/1982 15:15	58.72
20/02/1984 22:15	13.79	20/02/1984 22:00	13.86
18/01/1985 14:45	21.91	18/01/1985 14:45	21.97
26/08/1986 03:30	25.55	26/08/1986 03:30	26.56
05/04/1987 08:15	27.42	05/04/1987 08:15	27.45
06/01/1988 08:15	26.06	21/10/1987 08:45	26.63
06/04/1989 15:15	9.39	06/04/1989 15:00	9.47
28/02/1990 18:30	18.10	28/02/1990 18:30	18.19
08/01/1991 21:00	31.20	08/01/1991 21:00	31.31
05/01/1992 13:15	13.52	05/01/1992 13:15	13.64
11/06/1993 19:30	71.94	11/06/1993 19:15	73.15
05/10/1993 15:00	23.52	05/10/1993 14:45	24.49
25/01/1995 21:30	35.98	25/01/1995 21:30	36.09
18/02/1996 17:45	30.67	18/02/1996 17:30	30.75
19/11/1996 15:15	29.53	19/11/1996 15:15	29.81
09/04/1998 09:45	22.51	09/04/1998 09:45	22.64
05/01/1999 09:15	15.69	05/01/1999 09:15	15.76
12/01/2000 17:15	12.64	12/01/2000 17:15	12.72
08/12/2000 05:30	57.63	08/12/2000 05:30	57.70
18/05/2002 01:15	23.28	18/05/2002 01:15	24.04
15/11/2002 01:15	70.13	15/11/2002 01:15	70.51
02/12/2003 14:30	11.08	02/12/2003 14:15	11.14
08/01/2005 00:30	21.39	08/01/2005 00:30	21.46
03/12/2005 08:30	15.38	03/12/2005 08:15	15.52
15/11/2006 20:30	17.82	15/11/2006 20:30	18.08
31/03/2008 04:15	42.02	31/03/2008 04:15	42.57

Table C-5 – Broadmeadow Annual Maxima Series of Simulated Discharge – Table 1

Broadmeadow at Swords (Gauge No. 08008)			
2000 Urban Extent		2008 Urban Extent	
Date	Flow (m^3/s)	Date	Flow (m^3/s)
19/03/1964 20:30	17.23	19/03/1964 20:30	17.28
20/01/1965 10:15	36.26	20/01/1965 10:15	36.34
25/11/1965 11:15	53.17	25/11/1965 11:15	53.41
23/02/1967 01:15	39.56	23/02/1967 01:15	39.55
09/01/1968 03:00	33.40	09/01/1968 02:45	33.47
24/12/1968 20:15	52.10	24/12/1968 20:15	52.11
21/12/1969 02:45	9.29	21/12/1969 02:30	9.34
19/03/1971 04:30	39.22	19/03/1971 04:15	39.32
16/01/1972 02:30	11.48	16/01/1972 00:15	11.53
28/12/1972 17:00	24.82	28/12/1972 17:00	25.08
24/12/1973 02:00	18.95	24/12/1973 01:45	19.05
25/01/1975 10:45	20.77	25/01/1975 10:45	20.87
09/01/1976 10:45	13.16	09/01/1976 10:45	13.25
10/02/1977 19:15	21.32	10/02/1977 19:15	21.32
01/03/1978 15:45	9.60	01/03/1978 15:30	9.60
01/02/1979 12:45	40.94	01/02/1979 12:45	40.92
21/01/1980 12:30	46.80	21/01/1980 12:30	46.82
01/03/1981 21:30	16.98	01/03/1981 21:30	17.01
13/12/1981 21:00	35.01	13/12/1981 21:00	35.21
06/11/1982 15:15	59.32	06/11/1982 15:15	59.73
20/02/1984 22:00	13.94	20/02/1984 22:00	13.99
18/01/1985 14:45	22.02	18/01/1985 14:45	22.06
26/08/1986 03:15	27.64	26/08/1986 03:15	28.39
05/04/1987 08:15	27.48	05/04/1987 08:15	27.50
21/10/1987 08:45	27.52	21/10/1987 08:45	28.14
06/04/1989 15:00	9.56	06/04/1989 14:45	9.62
28/02/1990 18:15	18.28	28/02/1990 18:15	18.36
08/01/1991 21:00	31.42	08/01/1991 21:00	31.50
05/01/1992 13:15	13.77	05/01/1992 13:15	13.86
11/06/1993 17:45	74.61	11/06/1993 17:45	75.65
05/10/1993 14:45	25.52	05/10/1993 14:30	26.27
25/01/1995 21:30	36.20	25/01/1995 21:30	36.28
18/02/1996 17:30	30.83	18/02/1996 17:30	30.89
19/11/1996 15:15	30.10	19/11/1996 15:15	30.29
09/04/1998 09:45	22.77	09/04/1998 09:45	22.86
05/01/1999 09:00	15.85	05/01/1999 09:00	15.91
12/01/2000 17:15	12.80	12/01/2000 17:15	12.85
08/12/2000 05:30	57.76	08/12/2000 05:30	57.81
18/05/2002 01:15	24.82	18/05/2002 01:00	25.39
15/11/2002 01:15	70.88	15/11/2002 01:15	71.14
02/12/2003 14:00	11.21	02/12/2003 13:45	11.27
08/01/2005 00:30	21.53	08/01/2005 00:15	21.59
03/12/2005 08:15	15.68	03/12/2005 08:15	15.79
15/11/2006 20:30	18.35	15/11/2006 20:30	18.54
31/03/2008 04:00	43.20	31/03/2008 04:00	43.63

Table C-6 – Broadmeadow Annual Maxima Series of Simulated Discharge – Table 2

APPENDIX D

Supplementary Data from EVA Analysis

		1973			1995			2000			2008		
		D/E Combination			D/E Combination			D/E Combination			D/E Combination		
	Return Period [years]	GEV/LMOM	LP3/MOM/ LOG	LN2/MOM	GEV/LMOM	LP3/MOM/ LOG	LN2/MOM	GEV/LMOM	LP3/MOM/ LOG	LN2/MOM	GEV/LMOM	LP3/MOM/ LOG	LN2/MOM
Estimated quantile	2	8.539	8.47	8.226	10.017	9.888	9.62	10.111	9.974	9.716	10.127	9.951	9.71
	2.3	9.27	9.222	8.968	10.76	10.644	10.368	10.857	10.73	10.464	10.881	10.712	10.464
	5	12.802	12.888	12.806	14.189	14.202	14.12	14.294	14.295	14.215	14.344	14.321	14.244
	10	15.63	15.795	16.14	16.755	16.905	17.255	16.86	17.009	17.344	16.921	17.092	17.403
	20	18.348	18.536	19.538	19.079	19.375	20.364	19.181	19.494	20.441	19.243	19.646	20.534
	50	21.872	22.004	24.226	21.899	22.41	24.537	21.992	22.555	24.593	22.046	22.816	24.737
	100	24.518	24.548	27.96	23.882	24.579	27.784	23.965	24.748	27.819	24.006	25.104	28.006
	200	27.159	27.041	31.88	25.753	26.664	31.13	25.824	26.861	31.141	25.847	27.32	31.375
Goodness-of-fit statistics	SLSC	0.031	0.02	0.028	0.035	0.028	0.035	0.035	0.029	0.035	0.036	0.032	0.037
	PPCC1	0.988	0.989	0.979	0.987	0.986	0.977	0.987	0.986	0.977	0.986	0.985	0.975
	PPCC2	0.988	0.996	0.992	0.984	0.991	0.987	0.984	0.991	0.986	0.984	0.988	0.985
	LLM	-123.51	-122.98	-123.49	-123.84	-123.45	-124.08	-123.96	-123.56	-124.15	-124.34	-123.89	-124.43

Extreme value statistics for Owendoher derived from numerical modelling output for different urban extent

		1973			1995			2000			2008		
		D/E Combination			D/E Combination			D/E Combination			D/E Combination		
	Return Period [years]	GEV/LMOM	LP3/MOM/ LOG	LN2/MOM	GEV/LMOM	LP3/MOM/ LOG	LN2/MOM	GEV/LMOM	LP3/MOM/ LOG	LN2/MOM	GEV/LMOM	LP3/MOM/ LOG	LN2/MOM
Estimated quantile	2	4.035	4.276	4.03	4.57	4.871	4.571	5.39	5.697	5.399	6.383	6.658	6.392
	2.3	4.377	4.651	4.381	4.944	5.286	4.957	5.817	6.163	5.839	6.883	7.192	6.905
	5	6.322	6.574	6.402	7.08	7.401	7.186	8.213	8.527	8.327	9.614	9.887	9.725
	10	8.29	8.23	8.45	9.264	9.209	9.46	10.602	10.528	10.786	12.24	12.158	12.405
	20	10.611	9.909	10.832	11.864	11.03	12.119	13.382	12.53	13.588	15.199	14.421	15.362
	50	14.402	12.211	14.634	16.155	13.515	16.389	17.857	15.242	17.962	19.793	17.476	19.821
	100	17.97	14.035	18.114	20.233	15.476	20.321	22.007	17.369	21.886	23.905	19.865	23.691
	200	22.293	15.943	22.219	25.218	17.518	24.987	26.974	19.574	26.439	28.679	22.335	28.059
Goodness-of-fit statistics	SLSC	0.019	0.039	0.017	0.023	0.045	0.021	0.018	0.036	0.017	0.016	0.03	0.017
	PPCC1	0.998	0.987	0.998	0.996	0.984	0.997	0.998	0.985	0.998	0.998	0.988	0.998
	PPCC2	0.996	0.983	0.997	0.994	0.978	0.995	0.997	0.985	0.997	0.997	0.99	0.997
	LLM	-99.22	-100.72	-98.43	-103.38	-105.43	-102.61	-109.51	-110.97	-109.12	-116.49	-117.24	-116.23

Extreme value statistics for Griffeen derived from numerical modelling output for different urban extent

		1973			1995			2000			2008		
		D/E Combination			D/E Combination			D/E Combination			D/E Combination		
	Return Period [years]	GEV/LMOM	LP3/MOM/ LOG	LN2/MOM	GEV/LMOM	LP3/MOM/ LOG	LN2/MOM	GEV/LMOM	LP3/MOM/ LOG	LN2/MOM	GEV/LMOM	LP3/MOM/ LOG	LN2/MOM
Estimated quantile	2	24.717	24.55	24.382	24.937	24.744	24.598	25.176	24.954	24.831	25.346	25.103	24.994
	2.3	27.043	26.891	26.711	27.281	27.102	26.947	27.542	27.333	27.201	27.727	27.497	27.38
	5	39.048	39.152	39.07	39.363	39.459	39.388	39.712	39.798	39.738	39.961	40.039	39.986
	10	49.652	49.971	50.185	50.012	50.36	50.546	50.414	50.796	50.954	50.701	51.105	51.245
	20	60.751	61.126	61.837	61.133	61.599	62.215	61.567	62.135	62.657	61.878	62.515	62.978
	50	76.598	76.685	78.39	76.977	77.276	78.75	77.419	77.952	79.2	77.738	78.432	79.536
	100	89.675	89.2	91.939	90.023	89.886	92.25	90.441	90.675	92.676	90.745	91.235	93.005
	200	103.827	102.437	106.479	104.114	103.222	106.708	104.479	104.131	107.079	104.748	104.777	107.383
Goodness-of-fit statistics	SLSC	0.027	0.024	0.024	0.027	0.024	0.024	0.024	0.023	0.022	0.023	0.022	0.022
	PPCC1	0.988	0.989	0.987	0.988	0.989	0.987	0.991	0.992	0.99	0.992	0.992	0.991
	PPCC2	0.991	0.994	0.994	0.991	0.994	0.994	0.993	0.994	0.995	0.994	0.995	0.995
	LLM	-181.83	-180.86	-180.82	-181.84	-180.86	-180.82	-182.56	-181.59	-181.58	-182.83	-181.87	-181.86

Extreme value statistics for Broadmeadow derived from numerical modelling output for different urban extent

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